THE ELECTRIC CURRENT

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THE ELECTRIC CURRENT

THE

ELECTRIC CURRENT

HOW PRODUCED AND HOW USED

BY

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WITH 379 ILLUSTRATIONS

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PREFACE.

It is a somewhat trite remark that had the properties of Electric Currents, and especially of fluctuating currents, been discovered before the phenomena of Electrostatics, not only would the development of Electrical Science have been changed, but the whole of the nomenclature employed would have been profoundly modified. The attention o investigators, freed from the tyranny of action-at-a-distance theories, would have been fixed quite as much on the actions taking place in the surrounding medium, as upon those manifested in the conductors. What names would have been adopted to specify the various phenomena it is not easy to imagine, but it is almost certain that the word "current" would not have been used at all in the sense now attached to it. Instead, we should probably have had a nomenclature in which the part played in electrical phenomena by the medium surrounding conductors, would have been as prominently recognised as that played by the conductors themselves.

The following pages are an attempt to place before the reader the present position of Electrical Science by constituting the group of phenomena usually referred to as "effects" of the electric current, the central facts about which the subject is arranged. Certain it is that these "effects" have been by far the most fruitful, if not exclusively so, in the services which the so-called "Electricity" has been forced to render to mankind. Moreover, they present to the philosophical mind problems which transcend in interest, though inseparably connected with, those presented by the more early discovered phenomena. Necessarily the old names have been used throughout, for these are now too much ingrained and embedded in the literature of the science, as well as in the popular mind, to be displaced by more suitable ones. Mathematical symbols, though not absolutely tabooed, have been employed very sparingly, and will cause no trouble to the non mathematical reader. Instead of hiding the facts in such symbols, the attempt is made to give the reader a thorough grasp of the physical phenomena which underlie and justify the equations of the mathematician. How far the attempt has been successful others must judge, but no difficulty connected with the more recondite phenomena has been consciously shirked, and the author trusts that he has succeeded in making many of these clear to the average reader. The general plan of the work can readily be gathered from the table of contents.

The original intention was to have dealt fully and in detail, from the above mentioned point of view, with all branches of Electrical Science, but considerations of space, and the fear of exhausting the patience of the reader, have compelled the author most reluctantly to curtail his plan seriously. To take one instance only: it was intended in connection with electrostatic measuring instruments to deal fully with the subject of Electrostatics and electric strains in the medium. Room, however, could only be found for a very brief discussion. Then again, "Electric Waves," which were to have constituted an important section, have had to be treated very briefly. Numerous other instances of curtailment could be pointed out, but the author trusts that in the 750 pages here presented there still remains a very full, and in many directions a very detailed, account of the leading phenomena of Electricity and their modern applications. He may also perhaps hope that, should this attempt be favourably received, he may be permitted at some future time to complete his original plan.

In illustrating the historical sections, recourse has been had, wherever feasible, to the original diagrams of investigators, as being far more interesting than drawings of improved modern apparatus developed therefrom. In particular the researches of Gilbert, Volta, Coulomb, Faraday, and others have been so laid under contribution. But in respect of the modern position of the science, it is my pleasing duty gratefully to acknowledge the assistance which I have received in illustrating the text from numerous friends and electrical firms; more especially in the sections devoted to "Secondary Batteries," "Dynamos," "Measuring Instruments," and the "Applications of the Electric Current" am I indebted to this help for examples of the most modern apparatus and appliances. A full list of all these obligations would be tedious and perhaps uninteresting to the reader. In most cases the names of those whom I have to thank for the use of illustrations are mentioned in immediate connection therewith, and perhaps they will kindly accept this tacit acknowledgment of the obligation. But a more personal acknowledgment is due to Dr. S. P. Thompson and Mr. W. H. Preece for their great kindness in allowing me to use very freely the illustrations in their standard works on "Dynamos" and "Telegraphy and Telephony" respectively; and to the publishers of *The Electrician* and *The Electrical Review* for the use of numerous blocks of figures that have appeared in recent volumes of these journals.

I wish also to acknowledge that a number of the illustrations are taken from those originally drawn for Professor Ayrton's well-known Manual on "Practical Electricity," published by Messrs. Cassell and Company. In addition to those specifically referred to in the text, Figs. 169, 176, 179, and 183, were drawn from Professor Ayrton's own instruments, and it should be added that the Kelvin Galvanometer figured on page 343 embodies improvements due to the same successful inventor. Professor Ayrton also informs me that the Elihu Thomson Meter described on page 422 is founded on a patent taken out by himself and Professor Perry.

R. M. W.

1st September, 1894.

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THE ELECTRIC CURRENT:

How Produced and How Used.

Part I.

PRODUCTION OF THE ELECTRIC CURRENT.

CHAPTER I.

INTRODUCTION.

Throughout all ages the grandeur of the thunderstorm has excited the admiration, and oftentimes aroused the fears and superstitions of mankind, but it was not until a comparatively recent date (A.D. 1752) that Benjamin Franklin experimentally showed the connection between the lightning flash and an electrical experiment made nearly 2,400 years previously by an unknown philosopher. Thales of Miletus (B.C. 600) is said to have described the property of attracting light bodies which a piece of amber acquires when rubbed. For many centuries after Thales, nothing was done to investigate the cause of the attraction exercised by the rubbed amber, though a few observations bearing on the same subject were made and recorded. The first man who systematically repeated the observations of the ancients, and by greatly extending them became the founder of a new science, was Gilbert of Colchester, who in 1600 published a book in which he showed that the property possessed by the rubbed amber was also displayed by a vast number of other bodies. Not only did Gilbert thus become the founder of the science of Electricity, but he also gave the name to the science, for he it was who first used the term "electric," which he derived from the Greek name (ἤλεκτρον) for amber.

A different class of ancient observations, which previously to Gilbert had not been quite so barren of practical application, was that in which the earliest recorded fact was the attraction which the lodestone exerted on iron. It is doubtful whether the word *magnet* is due to the lodestone being first found by a shepherd named Magnes, as mentioned by Pliny, or to the circumstance that these black stones were first found near a town called Magnesia. Not only was it known in these ancient times that the lodestone attracted and sometimes repelled iron, but also that it could communicate this property to iron itself, or, as we now say, it could magnetise iron. The Chinese are supposed to have known, as early as A.D. 120, that a magnetised iron needle, when properly suspended, points approximately north and south, and the mariner's compass appears to have been used as early as the twelfth century, if not earlier. The "dip" of the needle was discovered in 1544 by Hartmann, and independently in 1576 by Norman, who made several ingenious magnetic experiments. Then we reach Gilbert, who in the work already mentioned much extended our knowledge of magnetic phenomena also, by numerous observations which we shall describe in the proper place.

From the time of Gilbert onwards the sciences of Electricity and Magnetism progressed slowly but surely along separate lines, and it was not until the present century that the long-sought-for link connecting them was found by the discovery of Oersted in 1820 that an electric current was able to influence a magnetic needle. The discovery of Oersted was followed by the brilliant investigations of Ampère and Faraday, and these, together with the results of the labours of a host of other workers in the same field, rapidly extended our knowledge of the properties of the electric current and the means by which it could be produced. These properties have proved so adaptive to the service of man that they have been seized upon by numerous inventors, who, hand-in-hand with pure scientists, have so effectually laboured at their task that to-day the electric current promises shortly to become the most useful, as it certainly is the most wonderful, of the servants of mankind. It has already profoundly modified the social relations of modern civilised life by giving us the electric telegraph, which enables the merchant to keep his hand upon the pulse of the world's markets, makes it possible for the traveller to be whirled along safely at the rate of seventy miles an hour, puts the journalist of Fleet Street in touch with the farthest corners of the earth, brings the diplomatists of all civilised countries into one vast presence-chamber, and, in various other directions too numerous to summarise, affects directly or indirectly the life of every citizen of every country into which it has penetrated, and makes its influence felt even in countries in which it is as yet unknown. In a minor way the electric current is changing our environment, by providing us with a brilliant and pure artificial light for our houses and streets, and is multiplying our artistic surroundings by means of the processes of electroplating and electrotyping.

But a social revolution even greater than that produced by the electric telegraph is now looming in the immediate future, in the possibilities underlying the electric transmission of mechanical power to a distance from the source where it is generated, and the distribution of large quantities of energy amongst a number of small consumers. What these possibilities are, has been well described by one of our leading statesmen, who naturally regards the question dispassionately from a statesman's standpoint, and without the enthusiasm of the scientist or the inventor. We think, therefore, that we cannot do better than place his views before our readers in his own words. He says:—

"I do not despair of the results that this distribution of force may scatter those aggregations of humanity which, I think, it is not one of the highest merits of the discovery of the steam engine to have produced. If ever it shall happen that in the house of the artisan you can turn on power as now you can turn on gas (and there is nothing in the essence of the problem, there is nothing in the facts of the science as we know them that shall prevent such a consummation from taking place, that distribution of power should be so organised), you will then see men and women able to pursue in their own houses many industries which now require the aggregation of the factory. You may, above all, see women and children pursue those industries without that disruption of the family which is one of the most unhappy results of the present requirements of the industries; and if ever that result shall come from the discoveries of Oersted and Faraday, you may say that they have done more than merely add to the physical force of mankind. They have done much to sustain that unity, that integrity of the family upon which rest the moral hopes of our race, and the strength of the community to which we belong."

In the following pages we propose to describe, with as much detail as may appear desirable, the numerous appliances by which the electric current has been adapted to the service of mankind, and at the same time to set forth, as far as they are known and without using abstruse mathematical formulæ, the principles which underlie the various phenomena with which we shall have to deal. We use the term "Electric Current" instead of "Electricity," because, as will appear in the sequel, the modern applications of electrical science to the arts almost without exception make use of the properties of "Electricity in motion," or the "Electric Current;" and it is seldom (and then chiefly for purposes of measurement) that the properties of electricity at rest are practically utilised. In fact, our chief concern will not be with that department of electricity which deals with pith-balls, Leyden jars, proof planes, glass-plate machines, and so forth, and which has been a source of wonder and delight to generations. Though still of great philosophical importance in all inquiries concerning the ultimate causes of electrical phenomena and the nature of electricity itself, and though it was the earliest to be submitted to strict scientific investigation, this part of the science must now yield the first place to its more vigorous offspring. We by no means intend to ignore the science of Electrostatics, or Electricity at rest, which will be briefly considered in due course; but we wish to emphasise throughout, that it is the *Electric Current*, and the phenomena directly connected with it, that have raised Electricity to the proud position of being one of the most potent factors in the everyday life of civilised nations, and, as far as we can foretell, in the future development of the human race. We shall, therefore, deal with the subject chiefly from the standpoint of the phenomena of currents; and in this way we hope to place within the reach of our readers a knowledge of the most recent discoveries and present state of the science of Electricity.

At the same time we shall endeavour, wherever possible, to set forth this knowledge in a quantitative form, so that the careful reader will not make the absurd and ludicrous mistakes in the estimation of electrical quantities which are even yet common amongst those whose daily occupation brings them more or less into contact with electrical phenomena. We should not have a very high opinion of a jeweller who attempted to weigh a diamond on the large weigh-bridge used for coal carts and waggons, or of an engineer who mistook a length of an inch or two for thousands of miles: and yet mistakes of even greater magnitude than these are still daily made with regard to electrical quantities by those who should know better. Perhaps now that electrical conductors are being laid in all the principal parts of our large cities, and a supply of electrical energy is being placed at the disposal of thousands of householders, these mistakes will tend to disappear. At any rate, it will be one of our aims to guard our readers against them, and to familiarise them as far as possible with the electrical magnitudes with which they may have to deal.

Still, we must not forget to do honour to those men whose labours have helped to bring the science to the position in which it stands to-day; and we propose, therefore, to commence with a brief historical sketch, reserving fuller historical details for those different parts of the subject to which they more intimately refer. Some parts of this historical sketch may not be at once understood by the reader who has no acquaintance with electrical phenomena; but it will be convenient to collect them here, where they can be easily referred to as the other parts of the book are being read.

HISTORICAL.

Gilbert.—The great work in which **William Gilbert** of Colchester described his epoch-making electric and magnetic experiments is entitled *De Magnete Magneticisque Corporibus et de Magno Magnete Tellure Physiologia Nova*, and was published in 1600. As was the fashion of those days, it was written in Latin, which was then the *lingua franca* of scientific men and of scholars throughout Europe. The Gilbert Club has recently had this important book translated into English, so that it is now accessible to our readers in their own tongue.

Gilbert's great success was due to his abandoning the methods of the old schoolmen, and following those methods which have made modern science what it is, and which were first clearly enunciated in the *Novum Organum* in 1620 by Lord Bacon; with whom Gilbert, as physician to Queen Elizabeth, must have been brought into intimate contact. The older scholastic method consisted in making all kinds of fanciful hypotheses about natural phenomena, but these hypotheses were never tested by experiment, which, indeed, was held to be unworthy of the attention of a true philosopher. It is only to the numbing influence of this absurd system that we can ascribe the long scientific lethargy which paralysed even the acutest thinkers of ancient Greece and Rome. Bacon dealt this system its death-blow, and contemporaneously Gilbert showed to the world, as the result of his own work in following a more common-sense system, a greater amount of scientific fruit than had been gathered under its rival during over two thousand years.

In Magnetism, Gilbert enriched the science with so many new ideas and experiments that we shall find it more convenient to refer to them when we are dealing with the subject of magnetism. In Electricity, he repeated and extended the observations of the ancients, and found that the property of attracting light bodies was not confined to rubbed amber, but that numerous other bodies when rubbed possessed the same property. Thus several precious stones (diamond, sapphire, carbuncle, opal, etc.), rock-crystal, glass, sulphur, gum-mastic, lac, sealing-wax, hard resin, arsenic, rock-salt, mica, and alum, behaved like amber. These Gilbert called "electrics." But he was unable to find that the following bodies were excited by friction, viz.:—emerald, agate, carnelian, pearls, jasper, chalcedony, alabaster, porphyry, coral, marble, Lydian stone, flints, hæmatites, corundum, bones, ivory, hard woods, metals, and lodestones. Not only were straws and light films attracted by electrified bodies, but also metals, stones, earth, wood leaves, thick smoke, and all solid and fluid bodies;

thus these attractions differed from that of the lodestone, which appeared to be confined to iron alone. Gilbert also observed that the production of electric properties is affected by the state of the atmosphere, dryness being favourable and moisture unfavourable, and that hot or burning bodies lost all traces of these properties.

Boyle and Guericke.—Robert Boyle, the inventor of the air pump and the discoverer of the well-known Boyle's Law in physics, and Otto von Guericke of Magdeburg, contemporaneously, about the middle of the seventeenth century, enriched the science with new facts. The former very much extended the list of known electrics, and the latter discovered that light and sound were produced by strong electrification. Guericke was also the first to observe the electrical repulsion of a light body which had touched an excited electric, and that a light body suspended near an electrified body, but without touching it, exhibited electrical properties. In most of his experiments he used as his source of electricity a ball of sulphur mounted on a spindle, the hand being employed as a rubber.

Newton and Hawksbee.—Sir Isaac Newton and Hawksbee, about the end of the seventeenth and beginning of the eighteenth century, enriched the science with several new and important observations. The former was the first to substitute a glass globe, still rubbed by the hand, for the sulphur ball employed by Guericke.

Gray.—A considerable advance was made by Stephen Gray, a Fellow of the Royal Society, by his discovery, in 1729, that certain bodies were capable of conveying (or as we now say *conducting*) electricity from one body to another. He first used a glass tube closed at the ends with corks; into one of these corks he fixed a fir rod, and at the end of the rod an ivory ball. On rubbing the glass he found that the ball attracted light bodies as vigorously as the glass itself. He altered the length of the rod, and also used a packthread hanging down from the upper storey of his house, but always obtained the same results. But he failed to carry the electricity horizontally along his packthread, until, at the suggestion of his friend Wheeler, he suspended the packthread by silk strings, when he was able to convey the electricity a distance of 886 feet, and to obtain all the usual effects at that distance from the excited electric. He also found that the human body and fluids were conductors. Previously to his discovery of conductivity Gray had extended the list of bodies which could be electrically excited by friction.

Du Fay.—Contemporaneously with Gray, C. F. C. Du Fay, of the Academy of Sciences, was working in France at the same subject. During the years 1733–1739 he discovered the insulating properties of glass, and repeated and confirmed Gray's experiments; by using wetted packthread, which he found to conduct more easily, he transmitted electricity along a string 1,256 feet long. But Du Fay's greatest discovery was that there were two kinds of electricity, which he named respectively *vitreous* and *resinous* electricity, because he found the former was produced by rubbing vitreous bodies, such as glass, and the latter by rubbing resinous bodies, such as amber, copal, gum, lac, etc. Wool, animal hair, rock-crystal, and precious stones, gave vitreous electricity, whereas silk, paper, thread, and many other bodies gave resinous electricity. The fundamental distinction was that bodies electrified with vitreous electricity repelled one another, but attracted bodies electrified with resinous electricity, the latter being also repellent to one another. Thus two electrified silk threads repel one another, but each will attract an electrified woollen thread, whereas two electrified woollen threads will repel one another. By means of an electrified silk thread it was therefore possible to distinguish whether an excited body was charged with vitreous or resinous electricity. If it attracted the silk thread, it would be charged with vitreous electricity; if it repelled it it would be charged with resinous electricity.

About this time (1740–1762) much attention was paid to the improvement of machines for producing electrification by friction, and various successful modifications were suggested by different Continental philosophers. Bose, of Wittenberg, added the prime conductor; Gordon, of Erfurt, a Scotch monk, substituted a glass cylinder for Newton's glass ball; Winkler, of Leipzig, replaced the hand as a rubber by a much more convenient cushion; Benjamin Wilson (1746) added the point collector; and Canton (1762) improved the rubber by smearing it with an amalgam of tin. Planta is supposed to be the first who substituted a plate of glass for Gordon's cylinder.

Morrison.—The first recorded practical application of the foregoing discoveries was made in 1745 by Charles Morrison, of Greenock, who devised and constructed an electric telegraph, which we shall describe later on (*see* page 563).

The Leyden Jar.—In the year 1745 a means of accumulating and storing up large quantities of electricity was independently discovered by Dean Kleist and by Cuneus and Pieter van Muschenbroeck of Leyden. Kleist made the discovery by accident. He happened to bring a medicine bottle, in the neck of which there was an iron nail, close to his electrical machine so that the nail touched the prime conductor. On withdrawing the bottle held in one hand from the machine, and touching the iron nail with the other, he received a violent shock.

Muschenbroeck was led to his discovery whilst endeavouring to find some means of preventing electric charges being dissipated. He thought that if he surrounded his charge by a good non-conductor, such as glass, he would attain his object. He therefore placed some water in a glass bottle and connected it by a wire to the prime conductor of his electrical machine. On turning the machine the water was duly electrified. Cuneus, who was holding the bottle, then attempted to disengage the conducting wire from the machine, when he received a violent shock which caused him to drop the bottle. The experiments were mentioned to Rollet, who introduced the term "Leyden Jar," and the new apparatus was rapidly perfected, receiving its present form of a jar coated inside and outside with tinfoil at the hands of Sir William Watson.

Franklin.—One of the greatest names in the development of electrical science is that of Dr. Benjamin Franklin of Philadelphia (*b.* 1706, *d.* 1790). His first labours were directed to the elucidation of the theory of positive and negative electricity first propounded by Sir William Watson, who gave the name of *positive* to the so-called *vitreous* electricity, and *negative* to the so-called *resinous* electricity of his predecessors. Franklin asserted that electricity is not created by friction, but is only transferred from one body to another. Thus, a body which becomes *positively* electrified receives its charge of electricity from one or more other bodies which will be found to be *negatively* electrified. In other words, positive electrification is due to an *excess* of electricity, and negative electrification to a *deficiency*. To prove this, Franklin showed clearly that in a charged Leyden jar the outside and inside coatings are oppositely electrified, and that exactly as much electricity is added on one side as is subtracted on the other. His experiments led the way to that mathematical development of the subject in which positive electricity is treated as an incompressible fluid. He also observed the power of points to discharge electricity.

For many years the analogies between lightning and the electric spark had been subjects of discussion amongst scientific men; and previous to 1750 Franklin had set forth these analogies in a paper in which he enumerated the electrical effects which were manifested by lightning. He waited some time for the erection of a tall spire in Philadelphia so that he might experiment on the subject, but whilst waiting the happy idea occurred to him that a kite sent up into the clouds and connected to the earth by a conducting string would serve his purpose as well or even better. So that it should not be destroyed by the rain, he constructed his kite of silk instead of paper, and fixed a sharp-pointed wire to the top to collect the electricity from the cloud. On the approach of a thunderstorm in June, 1752, he flew his kite in the ordinary way, and with ordinary twine for the string; at the end of the twine he tied a length of silk ribbon so as to insulate his hand from the conducting twine, and this ribbon was kept dry by being drawn under the cover of an open doorway. An iron key was also hung at the end of the twine. On the storm passing over, and when the twine had become well wetted, abundant sparks were drawn from the key, and all the electrical effects then known were observed, thus proving the identity of the lightning with the electricity of the laboratory. These experiments were repeated and confirmed by numerous observers in Europe. The practical outcome of Franklin's work was the elaboration of the lightning conductor to protect buildings from the destructive effects of thunderstorms.

Now that electricity at a high potential was brought within the reach of the experimenter, it was not long before an enthusiastic investigator fell a victim in the cause of science. Professor Richman, of St. Petersburg, on the 6th August, 1753, whilst observing the indications of an electrometer connected to a lightning-rod, was struck by a sudden discharge of electricity and immediately killed. His assistant, Sokoloff, was rendered insensible at the same time. This accident caused scientific men to be more careful in their experiments, but did not check their zeal.

Symmer.—In 1759 Robert Symmer revived Du Fay's theory in an improved form. He supposed, in opposition to Franklin, that there were two kinds of electricity, not however independent of one another, but co-existent. When a body was positively electrified, it had an excess of positive electricity, and when negatively electrified an excess of negative electricity. He supported his theory by an experiment which was long regarded as conclusive—namely, that on passing an electric spark through a sheet of paper the edges of the hole are turned up on both sides of the paper. Lichtenberg's electrical dust figures, which were discovered in 1777, were also regarded as supporting Symmer's theory. Symmer likewise discovered the electricity developed on silk stockings, and he describes various amusing phenomena which occur when two silk stockings of different colours which have been worn on the same leg are taken off and separated.

The pyro-electricity of crystals, and the electricity of fishes, particularly of the torpedo, were much experimented upon about this time, by numerous careful and industrious workers.

Cavendish.—The brilliant researches of Henry Cavendish should always occupy a prominent place in the science of electricity. Unfortunately he was so indifferent to fame that many of his experiments and results were never published, and were practically unknown until they were laboriously and independently discovered decades later by his successors. The first quantitative experiments on electrical resistance were made by Cavendish, who showed that a column of water of given dimensions offers as much resistance to the passage of electricity as an iron wire of the same cross-section but 400,000,000 times as long. In other words the resistance of the water he used was 400,000,000 times the resistance of iron. He also compared salt water with fresh, and showed that the former was

720 times a better conductor than the latter. Cavendish likewise made the first measurements of the electrical capacity of condensers, and discovered the law that with plates of glass coated with tinfoil the capacity varies inversely as the thickness of the glass and directly as the surface coated. He also used the electric spark in his brilliant synthesis of water. The decomposition of water by the electric spark was first effected by Van Troostwijk and Deiman.

The contributions of Cavendish to electrical theory, which he published in 1771, are very important. Amongst other things, by a very ingenious null method he proved, to a high degree of accuracy, the celebrated law of inverse squares.

Coulomb.—By his improvements of Mitchell's torsion balance (*see* page 102), Coulomb (*b.* 1736, *d.* 1806) provided electric and magnetic investigators with an instrument of precision which did much to facilitate the quantitative study of the phenomena. Coulomb himself industriously applied it to investigate numerous problems. He obtained measurements of the density of the charge at different points of the surfaces of various charged conductors placed either in contact or apart from one another. He also experimented on the dissipation of the charge of insulated bodies, and found that it was in great measure due to the moisture deposited on the surface of the insulators, though these latter showed signs of true conduction. The application of mathematical analysis to the problems investigated experimentally by Coulomb was made some years later by Laplace, Biot, and Poisson.

Galvani.—In 1790 Galvani made the very important discovery that when one end of a metallic conductor, such as a wire, is attached to the crural muscles and the other end to the lumbar nerves of a freshly-killed frog, violent muscular contraction is produced. He considered this to be due to a kind of Leyden jar discharge from the muscles, and that the nerves acted as conductors. This opinion was supported by the observation that the discharge of a very small Leyden jar through the limb also produced the contractions.

Volta.—Galvani's experiments were greatly extended by Volta, who, in 1793, showed that the contractions could be produced "by metallic touchings of two parts of a nerve only, or of two muscles, or even of different parts of one muscle alone," but that in these cases it was *absolutely necessary* that the conducting metallic arc should consist of two *different metals*. This discovery led him to his celebrated theory of Contact Force, and eventually in 1800 he produced the Voltaic pile. Thus was inaugurated the science of Galvanism, or Voltaic Electricity, which was supposed to deal with a new and different kind of electricity, but, as we shall see later on, this electricity is identical with the old frictional electricity. The great importance of the new discoveries, however, lay in the fact that they first pointed out a method of producing a continuous flow of electricity in a conductor, and thus led the way to that enormous development of the science due to the discovery of the various and unique properties of a conductor in which a current is flowing.

Davy.—The chemical action of the current in decomposing water was soon discovered by Nicolson and Carlisle in 1800, but no adequate explanation was afforded until Sir Humphry Davy supplied it in 1807, and utilised the new method of analysis in his brilliant researches on the composition of the alkaline earths and alkalies. In 1810 Davy also produced the arc light for the first time at the Royal Institution; he used carbon points as his electrodes, and a battery of 2,000 cells.

Oersted.—For many years scientists had been busily trying to find a connecting link between the phenomena of electricity and those of magnetism. The merit of the discovery belongs to Oersted of Copenhagen, who, in 1820, observed that a current of electricity flowing along a conductor deflected a magnetic needle placed in its neighbourhood. The discovery of Oersted was eagerly followed up in France by **Ampère,** who in an astonishingly short space of time extended it by numerous experiments, and built up a wonderfully perfect mathematical theory of the magnetic action of linear conductors carrying currents.

Seebeck.—A new, and, from a theoretical point of view, a most interesting department of electricity was opened up by the discovery in 1822 of a method of directly converting heat energy into electrical energy. Seebeck founded the science of thermo-electricity by showing that, in a complete metallic circuit made up of different metals, if the various junctions are artificially maintained at different temperatures a current of electricity will, in general, be found to flow round the circuit.

Here we close this brief historical sketch. The epoch-making discoveries of **Faraday**, which were published a few years later, together with the important researches to which they gave rise, belong to the domain of modern science, and it will be most convenient to discuss them in connection with the divisions of the subject to which they refer.

CHAPTER II.

METHODS AVAILABLE FOR THE PRODUCTION OF THE ELECTRIC CURRENT.

In the preceding chapter we have referred to the discoveries of Galvani, Volta, and Seebeck, which provide us with methods of maintaining a continuous flow of electricity in a conducting circuit as distinguished from the momentary flow which occurs in a wire when its ends are brought into contact with two oppositely charged bodies such as the inner and outer coatings of a charged Leyden jar. If, by any external means, the oppositely charged bodies could have their charges renewed as rapidly as they are discharged by the connecting wire, then a continuous current would flow along the wire, which would exhibit the same properties as a wire in which a current is maintained by a Volta's pile or by Seebeck's thermal arrangement. We shall subsequently prove that electricity, and also the electric current, however produced, are always the same, but we wish now to dwell more particularly on the properties possessed or effects exhibited by a conductor of electricity in which a steady current is flowing. These are of three kinds: **thermal, magnetic**, and **chemical**, and may be briefly described as follows :—

1. The **Thermal** effect.—The conductor along which the current flows becomes heated during the passage of the current. The rise of temperature of the conductor may be small or great according to circumstances; but some heat is always produced.
2. The **Magnetic** effect.—The space both outside

and inside the substance of the conductor, but more especially the former, becomes a "magnetic field"[1] in which delicately pivoted or suspended magnetic needles will take up definite positions, and in which certain materials known as magnetic become magnetised. Other secondary actions may also take place in this "field."

3. The **Chemical** effect.—If the conductor be a liquid which is a chemical compound of a certain class called *electrolytes*, the liquid will be decomposed at the places where the current enters and leaves it.[2]

These are the primary phenomena which are manifested when a steady continuous current flows; there are other phenomena attending the starting and stopping, and the rise and fall, of the current, which will be described subsequently.

Now, conversely, if a solid conductor exhibits the first two properties, or if a liquid conductor exhibits all three, we say that there is a current of electricity flowing in that conductor. It is important to notice that this last sentence enunciates one of the most convenient and easily understood ways of *defining* what we mean by an *electric current*. *If* the conductor exhibits these properties, there is an electric current in it; if it does not, then there is not. The phenomena, however, may be somewhat masked when the current is an alternating one, that is, when it consists of many currents alternately in opposite directions. For the present we postpone the consideration of this case. A less satisfactory way of defining a current would be to say that whenever two insulated conductors, equally but oppositely charged, are connected by a third conductor, a current of electricity passes along the latter, and the two former are found to be completely discharged. If the connecting body is not a conductor, then the two charged conductors retain their charges unaltered. The test by which the passage of the current is inferred is the unelectrified state of the originally charged conductors. The so-called passage of the current along the connecting conductor is almost instantaneous, and it is only by very delicate experiments that the three effects detailed above could be detected. But when, as already explained, the charges of the two insulated conductors are continually renewed as rapidly as a third conductor discharges them, the current becomes a continuous one, and it is far more convenient to fix the attention on the effects which this so-called current produces in and around the body which is said to convey it than to trouble oneself with phenomena belonging to a different branch of the science. In fact, if the discoveries of Galvani and Volta had preceded those of Thales, Gilbert, and the other philosophers to whom we have referred in the previous chapter, it is more than probable that the whole nomenclature of electrical science would have been entirely different. It is to the two-fluid and one-fluid theories of the eighteenth century that we owe such terms as "current," "conductor of electricity," &c.

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[1] We shall, later on, explain fully what is implied in this phrase.

[2] All chemically compound liquids are not decomposed by the current. Some, such as paraffin oil, turpentine, &c., do not allow the current to pass at all, and are practically insulators.

The reader will now understand that we provisionally use the term "electric current" as a convenient one, to denote a certain set of phenomena which occur simultaneously under certain conditions. The term arose out of those ideas on the nature of electrification which regarded an electrified body as containing a quantity of a special *fluid* called electricity. Now, although electricity in many cases undoubtedly behaves like an incompressible fluid, it is by no means certain that it is one; or, if it is, it is in a sense very different from that which was usually meant when the term was first applied to it. The answer to the question "What is electricity?" cannot be given in the present state of the science. Early experimenters, however, regarded it as a fluid, and when they observed that a body charged with this fluid lost all trace of it when joined to the earth by a metallic wire, it was very natural for them to infer that a current of the fluid had flowed along the wire, and to refer to what took place as a flow of electricity or an "electric current." The phrase is a convenient one, and is still used. The reader must, however, understand clearly that, for the present, we thereby neither assert nor deny the existence of an actual current in the conductor, but merely use the phrase as indicating that certain effects are produced *in the conductor, and in the space round it*, whilst the current is said to flow. But whatever electricity is, there is a true flow of electricity in the conductor. The progress of electrical discovery will probably modify the views at present tentatively held by scientific men as to the nature of electricity, and as to the ultimate explanation of the effects which occur in the conductor, and in the surrounding space, whilst the electric current flows in the conductor. But these effects will always be manifested whenever what is now called the electric current is maintained in the conductor.

Several methods of maintaining the current are known. The electric current itself can be accurately measured in several different ways which give concordant results. What is more important is, that the amount of mechanical or other energy that must be expended to maintain a particular electric current under given circumstances for a given time, can be both accurately calculated and accurately measured. In fact, electricity in motion, or the electric current, is a form of *energy* (or, more strictly speaking, of *power*, that is of energy in the act of being transferred from one form to another), and the general law of the conservation of energy applies to it. It is in this fact that we touch firm and well-known scientific ground, and it is on this account that, for the practical work of life, we can use the electric current and make all kinds of necessary calculations with regard to it, and the work that can be done with it, without committing ourselves to any particular theory regarding it.

Corresponding to each of the effects of the electric current enumerated above, there is a method of producing the electric current itself; or, to speak more accurately, we should say that there is a method of producing electric pressure or electromotive force which, if proper conducting circuits be provided, will give rise to electric currents. We must here anticipate the more complete development of the laws of the current which will form the subject of the next section, by explaining briefly that whenever a difference of electric pressure is, by any means, maintained at the two ends of a conductor, then an electric current will be set up in that conductor, and will continue to flow as long as the difference of pressure is maintained. Should the current not flow under these circumstances, then it will be found that the conductor employed contains within itself a source of back electric pressure, which is sufficient to neutralise the difference of pressure maintained at its two ends. Another law which we shall often tacitly assume is that steady electric currents can only flow in closed conducting circuits, that is, in circuits in which there is a continuous conducting path closed on itself like a ring or endless rope. The circuit need not be of the same conducting materials throughout, but should there be any non-conducting gap in it, the current will not flow. An apparent exception to this last statement occurs in the case of the electric arc, but we shall in the proper place give reasons for believing that the gap, whilst the arc lasts, is truly conductive.

Returning now to the methods available for producing an electric current, we have seen that whenever an electric current passes along a conductor, heat is produced in that conductor. On the other hand, if two pieces of different metals (say copper and iron) be taken, and one end of one joined to one end of the other, and the junction heated, the two free ends will be found to have different *electric pressures*, or, as it is usually expressed, these ends are at *different electric potentials.* If now the free ends of the metals be joined by a metallic wire, it will be found that an electric current will flow round the circuit formed by this wire, and the two original pieces of metal (in the case supposed, from iron to copper along the joining wire), as long as the original junction is kept hotter than the other junctions in the circuit. It should be noticed, however, that the conditions for producing the electric current by means of heat are more complicated than those for producing heat by means of the current. In other words, one phenomenon is not the simple converse of the other.

Again, when an electric current flows in a wire or other conductor, the space outside the conductor becomes a magnetic field. On the other hand, if a conductor be moved in certain ways, which we shall consider in detail presently, in a magnetic field, its two ends will be found to be at different potentials as long as the movement continues. If then these ends are suitably joined by a second conductor, an electric current will flow in the circuit formed by this new conductor and the moving conductor.

Finally, when an electric current flows through a chemically compound liquid conductor, the liquid is chemically decomposed at the points where the solid conductors, bringing the current to and leading it away from the liquid, make contact with the liquid. On the other hand, if two dissimilar metals be dipped into a chemically compound liquid conductor, or if two pieces of the same metal be dipped into two different compound liquids which are in conducting communication, in both cases the free parts of the two metals will be found to be at different electric potentials. And if these metals be joined by a metallic conductor, an electric current will flow through this metallic conductor and also through the liquids and other metals.

In describing in detail the various methods employed for generating the electric current on the above lines, we shall frequently have to refer to the laws which govern the transmutations of energy involved in the different processes. It will therefore conduce to greater clearness hereafter if we now devote a brief space to the consideration of these very important laws, which though far-reaching in their consequences, are not difficult to follow to the extent necessary to grasp their application to electric phenomena.

ENERGY.

The great fundamental principle with which we have to deal is that of the "Conservation of Energy." This principle, although it was not generally accepted until nearly the middle of the nineteenth century, is now one of the most firmly established principles of physical science. It asserts that energy itself is indestructible, although it may take various forms and be transferred from one agent to another. Thus, whenever energy appears at any place, we know that an exactly equal amount of energy, but not necessarily of the same form, has disappeared somewhere else. This must be regarded not as a mere theory, but as an experimental fact established by thousands of experiments, and not yet controverted by a single adverse one.

In works on dynamics it is explained that an agent that is capable of doing work possesses a store of energy, and that it is only because, and so far as, it possesses this store of energy that it is capable of doing work. The familiar illustrations usually adduced are that a raised clock-weight possesses a store of energy in virtue of its raised position, and in running down it will do a certain amount of work in driving the clock. Again, a moving hammer-head, just before it strikes a nail, possesses a store of energy in virtue of its motion; on striking the nail it is brought to rest and loses this energy, but does work in driving the nail. It should be observed that in both these cases the original stores of energy are ultimately converted into the heat form; in the case of the clock this heat appears at the pivots and rubbing surfaces of the teeth, &c., and in the case of the hammer it is distributed chiefly through the nail, the wood, and partly on the head of the hammer, though a very small portion of it becomes sound energy, and eventually assumes the form of heat energy in the various surrounding objects, some of which may be at a great distance. But none of the energy either of the raised clock-weight or the moving hammer-head is destroyed, although in these instances it takes a form in which it can no longer be made serviceable to man. This tendency of energy to assume forms unserviceable to man is known as the "dissipation" of energy, a principle correlative to, and intimately associated with, the doctrine of the conservation of energy. It would, however, lead us too far from our present subject if we attempted to discuss the doctrine of the dissipation of energy in all its bearings, and we must therefore leave it.

Returning to the main doctrine of the conservation of energy, we observe that whenever work is done energy is *transformed*, and is often in great part transferred from the body which originally possessed it to other bodies, some of which may be at a great distance from the first body. Also the total work that can be got from any body or system of bodies is the proper measure of the "available energy" which it possesses, although in most cases it is less than the total quantity of energy which the body or system may contain.

Now we have asserted above that electricity in motion, or the electric current, is a form of energy. Two lines of reasoning and experiment justify this assertion. In the first place, as we shall see more fully as we proceed, we can only procure a continuous electric current by the continuous expenditure of energy. Secondly, from electricity in motion various forms of energy can be procured. Thus in the thermal effect we obtain, as a direct result, heat energy in the conductor. Again, by making use of the magnetic effect we can either, as in electric motors, obtain mechanical energy, or, as in telephones, obtain energy in the form of sound-waves. Then again, in producing the chemical effect, the decomposed constituents of the compound liquid possess a store of energy of chemical separation. These instances, when regarded from the standpoint of the doctrine of the conservation of energy, suffice to prove that electricity in motion, which can only be procured by the expenditure of energy, and in its turn gives rise to various forms of energy, must itself be one of the forms of energy.

We shall now describe in detail the various methods used for the production of the current, but shall not take them in the order in which we summarised them on page 17. It will be more convenient to commence with chemical methods of producing the current, because these methods were the first by which continuous currents were produced, and they are still extensively employed for many purposes. Next the magnetic methods of producing the current will be considered, for these are the most important in the widening development of the applications of the electric current to the service of mankind. Lastly, we shall treat briefly of the thermal methods of producing the current—methods which have not yet risen to a position of much practical importance.

CHAPTER III.

CHEMICAL PRODUCTION OF THE CURRENT.

One of the largest stores of energy that are at the disposal of man, and upon which he can draw when he wishes to have work done for him, is the energy of chemical separation. The energy of coal or, more strictly speaking, of coal and air, is of this kind. The carbon of which the coal chiefly consists has what chemists call an *affinity* for the oxygen of the air, and in virtue of this affinity the atoms of carbon and oxygen in certain circumstances rush together to form complex molecules of carbon dioxide or carbonic acid gas. This process is what is popularly known as *burning* the coal or carbon. In the rush of the atoms together and the collisions consequent thereupon, a definite amount of heat energy is developed, and instead of the store of energy due to the separated atoms of carbon and oxygen, we have now the more active energy of a definite quantity of heat which we can use to drive our steam engines and to do our work. The carbon dioxide, after it has given up its heat by radiation or otherwise, has no longer the same store of energy that the separate atoms of carbon and oxygen possessed before they combined; and whatever be the nature of chemical affinity, the predisposing cause of the combination, we know by experiment that, in order to separate the molecules of carbon dioxide again into the constituent atoms of carbon and oxygen, we must provide from other sources a quantity of energy exactly equal in amount to the heat energy which appeared when combination occurred. In this way, and in this way only, can we get back our separate atoms.

But carbon is not the only body which has an affinity for oxygen and can be burnt or oxidised in it. Nearly all the bodies known to chemists as elements have a greater or less affinity for oxygen, and can be caused to combine with it, and the measure of the affinity is the amount of heat energy produced when definite quantities of the body combine with the equivalent quantities of oxygen. The bodies resulting from the combination are technically known as oxides, and the process as oxidation; but in the utilisation of the energy of chemical separation for the direct production of electrical energy, the oxidation is usually accomplished at a low temperature, and further combinations are allowed to take place by which bodies more complex than oxides are produced, and a greater amount of energy dealt with. It may be taken as a general rule that when a series of bodies increasing in complexity are formed in a series of successive reactions, which take place without the supply of external energy, the amount of heat or other energy produced increases with the complexity of the product. As an example take zinc. The combination of one pound of zinc (Zn) with the equivalent quantity of oxygen to form zinc oxide (ZnO), the zinc-white of painters, sets free a measurable amount of energy. But zinc oxide can indirectly be caused to combine with sulphur trioxide (SO_3) and form zinc sulphate ($ZnSO_4$), and in this second combination a further amount of energy is set free.

When we are dealing with heat energy, it has been found that the most convenient way of measuring any particular quantity of heat is by estimating the quantity of water which the heat in question would raise one degree in temperature. That is, we take as our unit of heat the quantity of heat that will raise one gram or one pound (according to the unit of mass adopted) of water at its point of maximum density (4°C.) one degree Centigrade in temperature. If the gram be taken as the unit of mass, then the corresponding heat unit is called the *calorie;* no name has as yet been given to the pound heat-unit, and it will therefore conduce to conciseness of expression if we make use of the calorie. The transformation to any other heat-unit is, however, only a question of arithmetic, and can be made by using the proper numerical multiplier. Now in the process of oxidising 65·5 grams of zinc to the form of zinc oxide, experiments, which will be found described in any good book on physics, show that heat to the amount of 85,800 calories is generated; and in the combination of this zinc oxide with sulphur trioxide to form zinc sulphate, 59,400 more calories are generated. These numbers measure the available energy of chemical separation of the materials before the combinations take place. Thus if all the energy of chemical separation is allowed to assume the form of heat, there would be about 41 per cent. less heat produced by turning 1 lb. of zinc into zinc oxide than by turning 1 lb. of zinc into zinc sulphate, even if we neglect in the latter case the heat produced by the formation of the sulphur trioxide. The readiest way of making zinc sulphate from zinc is to dissolve it in moderately dilute sulphuric acid (H_2SO_4), commonly known as oil of vitriol. The net result of the chemical changes that take place is expressed by the *chemical equation*:—

$$H_2SO_4 + Zn = ZnSO_4 + H_2$$

which is simply chemists' shorthand for saying that sulphuric acid (H_2SO_4) added to zinc (Zn) produces zinc sulphate ($ZnSO_4$) and hydrogen gas (H). Probably the actual changes are more complex, but we are now only concerned with net results. But the molecules of zinc sulphate and hydrogen have less energy of chemical separation as a system, if they have any such energy at all, than the system of molecules of sulphuric acid and zinc from which they were formed. The energy of chemical separation which has disappeared is not, however, destroyed, but takes some other form. If the experiment be performed by throwing scraps of zinc into the diluted acid, the energy of chemical separation that disappears reappears as heat energy, for the liquid and the containing vessel become warmed. We shall presently show how it may be made to assume an electrical form of energy, but before doing so a few historical notes on the rise and development of this method of producing the current may prove interesting.

HISTORICAL.

We have already (page 14) alluded briefly to Galvani's important discovery in 1790, and to Volta's work, which immediately followed. These two celebrated philosophers held very different views as to the causes of the phenomena with which they dealt. Galvani ascribed the effects to "animal electricity" produced by the nerves and muscles of the frog experimented upon, whereas Volta held that the electrical manifestations were due to the "contact force" at the metallic junction of the two dissimilar metals which he found were necessary if only two parts of the *same* muscle were touched. With the substitution of "chemical action" for animal electricity, the controversy has extended down to the present day, and though in the intervening years many points formerly hotly contested have been settled, there are still some outstanding problems upon which physicists are not yet quite agreed.

In attempting to prove his point that electricity was actually developed by the contact of dissimilar metals, Volta invented the condensing electroscope shown in Fig. 1. This consists of two circular metal plates, the upper one attached to an insulating handle, whilst the lower one is fixed to a brass rod, which, passing through the neck of the glass globe, supports two gold leaves at its lower end. Two rods of different metals, say copper and zinc, are now soldered together end to end so as to form a single compound rod. The zinc end of this rod is held in one hand and the copper end is brought into contact with the lower plate of the electroscope; the upper plate, which at the time is resting upon the lower plate, is touched for an instant with the other hand, which is then removed. The metal rod being taken away, and the upper plate lifted by its insulating handle, it is found that the leaves of the electroscope diverge, indicating, as may easily be shown, that the plate and leaves have become charged with so-called negative electricity. Volta also found that if the plate of the electroscope were made of copper, and if the end of a rod of zinc were brought down upon it, but with a piece of cloth moistened with acidulated water inter posed, the same effect was produced.

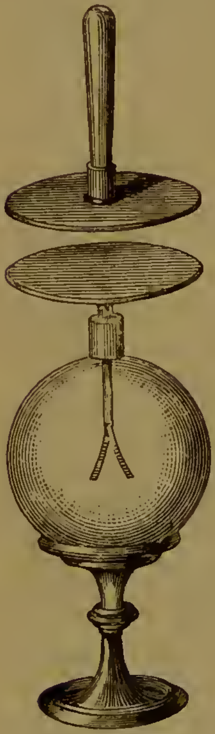

Fig. 1.—The Condensing Electroscope.

From these experiments Volta concluded that an electric *tension*, or as we now call it, an *electromotive force*, is developed whenever two inert metals, like copper and zinc, are brought into contact. He quite overlooked some of the attendant circumstances of the above experiments, more especially the action of the moisture of the hand on the zinc in the first case, and of the acidulated water on it in the second case. In fact, in 1795, Wells had shown that the presence of certain conducting liquids, notably the mineral acids and water, in contact with the dissimilar metals, was necessary to the success of the experiments. Volta also overlooked the fact that in the air of the room the two metals were surrounded by an oxidising medium which would tend to act more strongly on the zinc than on the copper.

Following up these experiments, Volta found that the observed effects, whether electroscopic or muscular, were very much increased by increasing the number of metallic junctions in the conducting arc, provided that the ends of the bi-metallic pieces were connected by liquid conductors. The conditions of this experiment will be best understood by reference to Fig. 2, which is reproduced from one of Volta's papers. He gives it the name of the "Crown of Cups." The arched bars *CaZ* are formed of two different metals, the part *Ca* being of copper, and the part *aZ* of zinc. The cups contain pure water, or salt water, or lye, and it will be observed that into each of them, except the two extreme ones, the inserted ends of two consecutive bars are zinc and copper respectively. This arrangement of Volta's is in fact the typical arrangement of a modern one-fluid primary battery, as will be seen at once by comparing it with Fig. 3, which illustrates the latter. The chief difference between the two forms is that in the more modern one the parts of the metallic arches that are inserted in the liquids are made of large flat plates instead of being mere continuations of the curved portions. In the older form, however, the ends of the conductors immersed in the liquid appear to be flattened out. Also by the insertion of a single zinc plate into the jar at one end, and a single copper plate into the jar at the other, the contents of each jar are

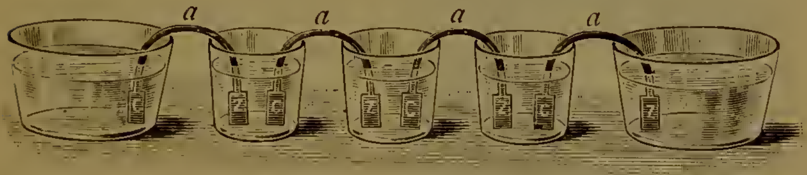

Fig. 2.—Volta's "Crown of Cups."

made exactly similar in the modern form, and the loose wires extending from these terminal plates are ready to make the connections for any desired experiment.

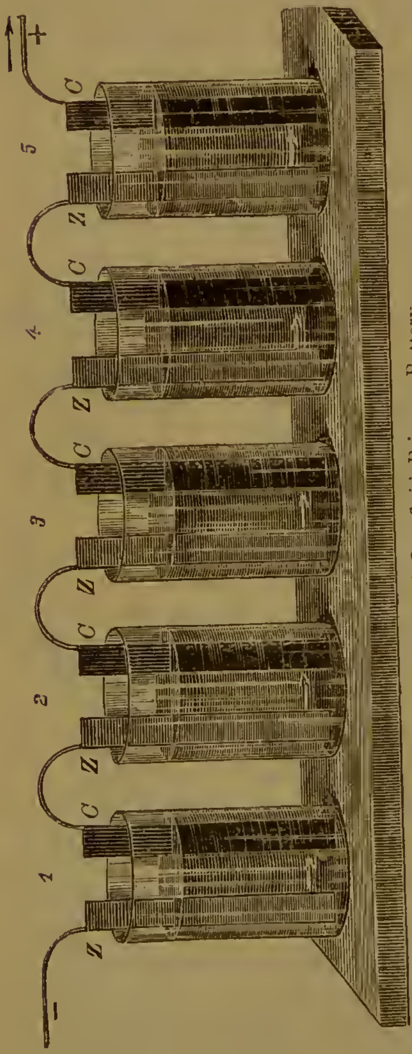

Fig. 3.—Typical One-fluid Primary Battery.

But Volta produced a very much more compact form of his arrangement of bi-metallic conductors electrically connected by moisture, to which, on account of its shape, he gave the name of the "Pile," a name which is still used for batteries in France. An early form of this very important piece of apparatus is illustrated in Fig. 4; the metallic parts consist of a number of discs of zinc and copper of the same diameter, and these are built up as shown in the figure, in which the copper discs are marked *C* and the zinc ones *Z*. The two metals occur alternately. The lowest disc is of copper; over this is placed a disc of zinc; between this and the next disc of copper, however, is interposed a thin layer of card or leather moistened with acidulated water. On this is placed the disc of copper, then another of zinc, then a disc of moistened card, and so on. The order is always zinc, moistened card, copper, which is continually repeated. The number of discs that can be used is only limited by mechanical considerations of the stability of the pile, and to steady it the four vertical rods, *m*, *m*, seen at the sides, are used. These must be of non-conducting material. It is found that the electric pressure between the lowermost zinc plate and the uppermost copper is proportional to the number of "elements," consisting of zinc, moistened card, copper, which make up the "pile." The vessel of liquid connected to the lowermost copper disc was used by Volta to make connections from the pile to external apparatus. In the completed pile a similar vessel was connected with the topmost copper disc.

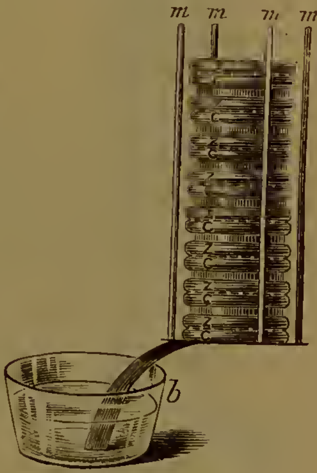

Fig. 4.—Volta's First Pile.

The final form of the pile is shown in Fig. 5, where the supporting columns are reduced to three, which are mechanically sufficient, and the discs can be clamped tightly together by the wooden disc at the top. The terminal beakers of liquid are replaced by wires soldered to the terminal discs, and provided with binding screws for greater convenience in making connections.

Volta's pile, though extremely interesting historically, is not of much use as a current producer, because the sheets of moistened card interposed between the metals cut the current down by the high resistance (*see* page 41) which they offer to its flow. But improvements were soon introduced, which had the effect of diminishing this resistance. The earliest of these was made by Cruikshank, who, in 1801, introduced the battery shown in Fig. 6. The trough is divided into a number of separate compartments by compound rectangular sheets of copper and zinc soldered together back to back, and so placed in the trough that all the coppers face to the right and all the zincs to the left. A loose sheet of copper (Cu) is placed in the last compartment on the left and a loose sheet of zinc (Zn) in the last on the right. The various compartments are now filled with dilute sulphuric acid. On consideration it will be seen that this is simply a Volta's pile set horizontally, and with the moistened card replaced by dilute acid, which is a much better conductor; it therefore gives, under the same external circumstances, a much stronger current than a pile consisting of the same number of plates of zinc and copper; but the current soon falls off. Moreover, there is considerable chemical action when the battery is not sending a current, and to avoid this the acid should be emptied out when the battery is not in use.

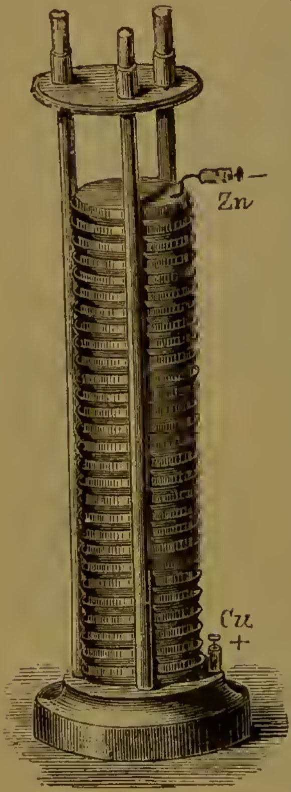

Fig. 5.—Volta's Pile.

In 1815 Wollaston introduced the much-improved

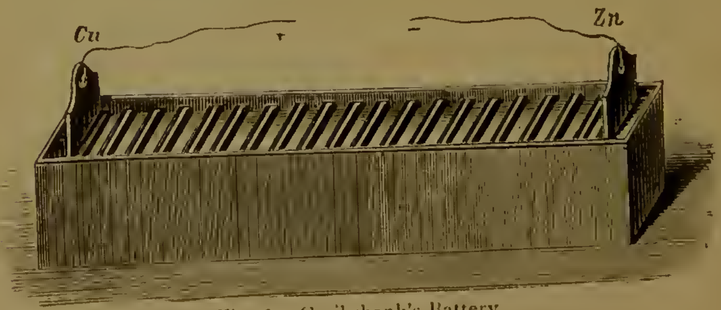

Fig. 6.—Cruikshank's Battery.

battery shown in Fig. 7. Instead of Cruikshank's single trough, divided more or less completely into separate compartments, Wollaston, returning to Volta's earlier form (Fig. 2), used a separate cell (in this case of glass or porcelain) for each pair of plates, a practice which has ever since been universally followed. The plates themselves consisted of rectangular blocks of zinc, *z z*, and U-shaped sheets of thin copper. The zinc of one cell was joined to the copper of the next by a band of copper, *m*, and kept from touching the copper of its own cell by strips of wood which were wedged in between them. The copper bands, *m*, were rigidly attached to the wooden framework, K, so that, when not in use, wasteful chemical action could be stopped by lifting the plates bodily out of the acid, a plan much more convenient than emptying the acid out of the cells.

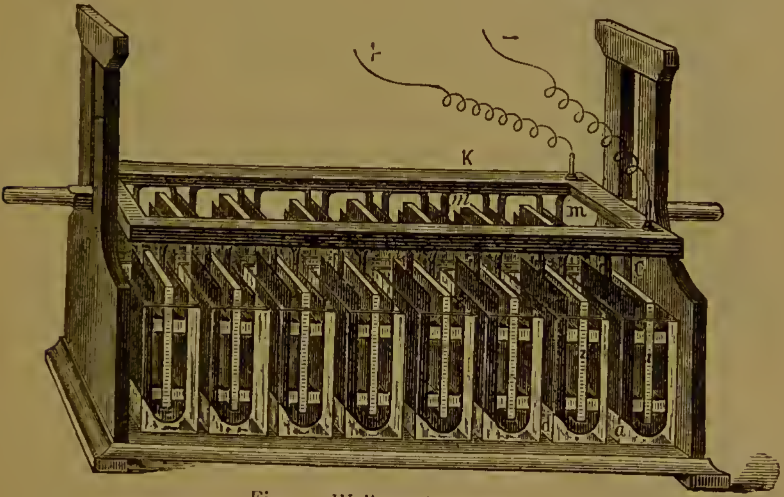

Fig. 7. -Wollaston's Battery.

In Wollaston's cell, the peculiar shape given to the copper, by which it almost completely surrounds the zinc, tends very much to diminish the internal resistance of the cell by the increased cross-section of the path along which the current travels. This idea was carried further in 1822 by Hare, of Philadelphia. He placed a large sheet of zinc on a large sheet of copper, and separated them from one another by narrow strips of cloth; these were then rolled up as shown in plan in the lower part of Fig. 8, and mounted over a trough of acid into which the roll could be lowered when a current was required. On account of its very low resistance, due to the large surfaces of copper and zinc and the short distance between them, this cell could give a very large current, which exhibited powerful heating effects. The cell was therefore known as Hare's Deflagrator.

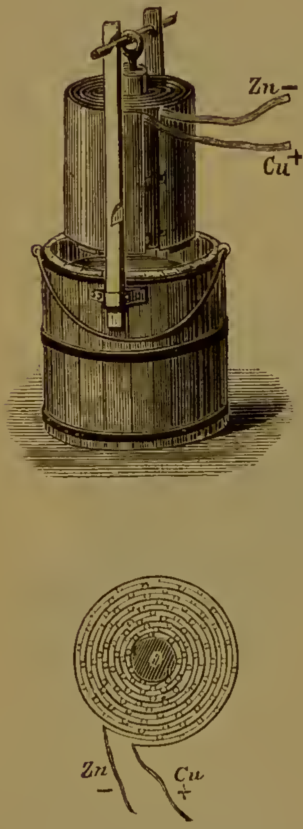

Fig. 8.—Hare's Deflagrator.

In all the above cells, wasteful chemical action takes place if the plates are left in the liquid when no current is being taken from them. This defect is technically known as "local action," and is due, as we shall presently see, to the fact that the surfaces of the zinc plates are not of uniform hardness, and also that minute impurities are embedded in them. Sturgeon, in 1830, discovered that this local action could be very much diminished by "amalgamating" the zinc plates with mercury. To do this, the plates are first cleaned by dipping them in moderately strong sulphuric acid, and then mercury is rubbed over their surfaces with a rag tied on the end of a stick. After this treatment a much more uniform surface is exposed to the action of the acid, and the zinc is not attacked so vigorously when no current is flowing.

Another fault in these early cells is the rapid falling off of the current in the first few minutes after the external circuit is completed. This is due to "polarisation," which was first successfully dealt with by Daniell, who, in 1836, produced a cell which is still largely used.

EXPLANATION OF TERMS.

Before we describe the modern forms of galvanic batteries we must explain a few of the terms which we shall frequently have occasion to use. Hitherto we have only spoken of the "electric pressure" between the two ends of Volta's various contrivances. We must now indicate what this means. Before Galvani's and Volta's discoveries, the only methods of obtaining electrical effects, in addition to those due to thunderstorms, &c., depended upon the friction of various bodies called "electrics." By these means insulated conductors could be charged with what was called electricity, which in all these early experiments certainly behaves as if it were an incompressible fluid. Franklin regarded so-called *positively* charged bodies as possessing an *excess* of this fluid, and the so-called *negatively* charged bodies as being *deprived* of part of their proper quantity, whereas uncharged bodies simply possess a normal amount of it. This is the view which is most in accordance with modern ideas. By means of the effects they produce, the various charges were capable of more or less exact measurement. Also when a conductor, charged with a certain quantity of positive electricity, is joined by a metallic wire to a conductor charged with an *equal* quantity of negative electricity, all trace of electrical action disappears. This process was called *discharging* the conductors, and during the operation electricity passes along the wire from the positively charged body to the negatively charged body. This passage constitutes the so-called *current of electricity*, and the immediate influencing cause of the flow of the electricity was the *electric force or pressure* which, before the bodies were joined, had been set up between them in the process of charging.

Now, if the conductors joined to the two ends of a voltaic pile are examined for electrical effects, it is found that the one joined to the copper end behaves as a body feebly charged with positive electricity, and that joined to the zinc end behaves as a body feebly charged with negative electricity. If, therefore, these two bodies are joined by a conducting wire, a current of electricity should flow from the copper to the zinc; and such is, in fact, the case. But now occurs the phenomenon in which the pile differs from the older methods of producing electrical effects. If the copper and zinc ends be disconnected they will be found to be still charged with as much electricity as at first, instead of being discharged as in the experiment previously described. In fact, if an *electrometer*, which is an instrument for measuring electric pressure, be applied to the copper and zinc ends, even whilst joined by a conductor it will be found that there is a difference of electric pressure, or, as it is usually called, a *difference of electric potential* between them. No such difference of potential will be found after the connection is made between the positively and negatively charged bodies referred to in the last paragraph. Now electric pressure, or **potential difference**, however produced, measures simply *the* **tendency** *of electricity to flow from the point where the potential is high to the point where it is lower.* The flow will always take place *if a conducting path be provided between the two points.* By a conducting path is meant a path along which electricity *can* flow, and it is a matter for experiment to decide what materials can supply this path. It follows that a continuous flow of electricity must be taking place along the conducting wire from the copper to the zinc; in other words, there is a continuous *electric current* along the wire. In fact, the pile renews the potential difference at the two ends of the wire as rapidly as it is destroyed by the flow of the electric charges along the wire. In this way a continuous current of electricity is maintained in the wire. But we have already seen that a continuous electric current can only be maintained by an expenditure of energy. In this case the pile supplies the energy which maintains the current, and this energy is obtained from the slow oxidation or burning away of the zinc, due to the action of the acid in the moistened card upon it.

The typical simple voltaic cell (Fig. 9) behaves in exactly the same way. If the conducting wire, CZ, be removed, it will be found that the ends C and Z connected to the plates are feebly charged with positive (+) and negative (—) electricity respectively, and thus when they are joined a current of electricity flows from C to Z. As in the pile, the current continues to flow because the charges at C and Z are renewed as rapidly as they are discharged, and the energy of the current is supplied by the slow combustion of the zinc in the cell. But, as we have already said, electricity behaves as an incompressible fluid. If, therefore, it is continually flowing from C to Z it cannot accumulate at Z, but must return to C by the only other conducting path open—namely, down the zinc plate, Zn, through the liquid to the copper plate, Cu, and thus back to C. The battery thus behaves as a pump which is continually pumping electricity

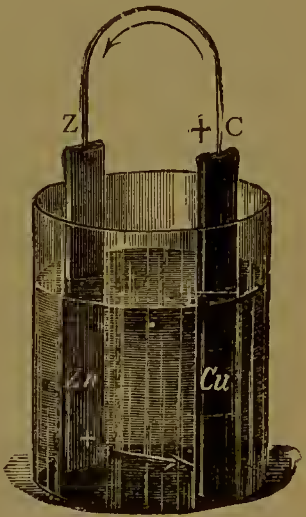

Fig. 9.—Typical Voltaic Cell.

round this circuit. But whereabouts in the circuit is the pump situated? We have seen that the *energy* of the current is derived from the slow combustion of the zinc. It seems, therefore, natural to suppose that the driving power which pumps the electricity round the circuit is situated at the place where this combustion is going on—that is, at the zinc-acid junction—and that this is the *seat of the electro-motive force* (or electric pressure) in the cell. This view is supported by the fact first pointed out by Sir William Thomson that the magnitude of the electro-motive force can be, at least very approximately, calculated from the thermal values of the chemical reactions that take place in the cell. In other words, since we know the heat-value of the combustion of one gram or one equivalent of zinc, and the quantity of electricity that is set in motion when this zinc is consumed, we can calculate the value of the *tendency* there is to set electricity in motion—that is, the *electro-motive force*, or the *electric potential difference*, or the *electric pressure* developed—when zinc is brought into contact with an oxidising medium. This electro-motive force always acts in the direction *from* the zinc *towards* the oxidising medium, and is measured in terms of a unit called the **Volt**, which for the present we shall simply regard as a unit in which electric pressures can be measured. It will be accurately defined later on. In the same way, the electric potential-difference existing between *any* oxidisable body and the oxidising medium in which it may be placed can be calculated (*see* page 45), and this is always such that when the circuit is closed the electricity tends to flow from the oxidising medium to the oxidisable body in the external part of the circuit, and from the oxidisable body to the oxidising medium across the junction. Now copper is oxidisable, but not as easily as zinc. There is therefore an electric pressure at the copper-acid junction (Fig. 9) tending to drive electricity from the liquid to the copper round any external circuit, and from the copper into the liquid across the junction. This pressure acts against the pressure at the zinc-acid junction, and is a disadvantage, as the effective pressure in the circuit can thus only be the difference of the pressures at the two junctions. It is as if we had two pumps at work in the circuit; a strong one at the zinc-acid junction pumping the electricity round in one direction, and a feebler one at the copper-acid junction trying to pump it round in the opposite direction, and therefore diminishing the flow. We shall return to the consideration of this point again, but meanwhile we must caution our readers that the above view of the position of the *electro-motive force* in the voltaic circuit is not held by all physicists. Some following Volta's ideas of "Contact Force" consider the electro-motive force as placed at the point Z, where the dissimilar metals, the copper of the conducting wire, and the zinc plate of the battery, are in contact. The problem, though at first sight extremely simple, is not easily settled by direct experiment. A full discussion of the various arguments in the controversy would lead us far beyond the plan of this book.[1] All authorities are, however, agreed that the *energy* is taken into the circuit at the zinc-acid junction, and is due to the combustion of the zinc. This is the main fact to keep in view.

Resistance is another term that we shall frequently use. It is found that the magnitude of the current that flows from C to Z (Fig. 9), when they are joined by a conductor, depends upon the *dimensions* and *material* of the conductor. If a short thick copper wire be used, a greater current will pass than if a long thin one be employed, for an increase of length increases the resistance, whereas an increase of thickness diminishes it. Again, with a copper wire, a greater current is obtained than with an iron or German-silver one of the same dimensions. The physical property of the conductor which thus influences the current is called its *resistance*, and the lower the resistance the greater is the current set up in the case cited. But the plates and fluid of the cell are also part of the circuit, and have to provide part of the path for the current, which experiment shows is affected by altering the size of the plates or the concentration of the liquid. There is thus an *internal resistance* in a voltaic cell which affects the magnitude of the current, and when large currents are required this internal resistance should be made as small as possible. The unit in which resistance is measured is called the **Ohm**. (*See* page 276.)

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[1] The student who cares to pursue the subject will find it exhaustively dealt with in a paper by Dr. O. J. Lodge "On the Seat of the Electro-motive Force in a Voltaic Cell" (*vide Journal of the Society of Telegraph-Engineers*, Vol. xiv., 1885, pp. 186 *et seq.*). The arguments against Dr. Lodge's views will be found in the discussion which followed the reading of the paper.

It is also important to understand clearly the *nomenclature* usually employed in referring to the various parts of a voltaic cell. We have seen that *inside* the cell the current flows from the plate at which the chemical action is more energetic to the plate at which it is less energetic. Thus, in Fig. 9 the current inside the cell flows from the zinc plate, *Zn*, to the copper plate, *Cu*. The former is therefore called the *positive* (or +) plate of the battery, and the latter the *negative* (or —) plate. But *outside* the battery the current flows from the terminal or *electrode* C connected with the negative plate to the electrode Z connected with the positive plate. The former electrode is therefore called the positive (+) terminal of the battery, and the latter the negative (—) terminal. Thus, the *negative terminal or electrode* is connected to the *positive plate*, and the *positive terminal or electrode* to the *negative plate*. This sometimes leads to confusion amongst those who are unaccustomed to batteries, but the distinction is easily grasped if the attention be fixed on the direction of the current in the different parts of the circuit. The names of the *plates* have reference to the course of the current *inside* the cell, whereas the names of the terminals or *electrodes* have reference to the course of the current *outside* the cell.

POLARISATION.

The batteries we shall next describe have most of them been devised with a view to overcome more or less completely one of the most troublesome drawbacks of the early batteries, namely, "polarisation." The few exceptions consist of batteries devised for special purposes, where either polarisation is in itself immaterial, or where only very small currents are required, and therefore, as we shall see, very little polarisation can take place. In batteries which "polarise," the current is not long maintained at the strength which it has when the circuit is first closed, but falls off at first rapidly and afterwards more slowly. The larger the initial current, the more rapid is this falling off. The evil is due to one of the fundamental properties of the current, namely, the chemical effect which is always produced when a current of electricity passes from a solid to a chemically compound liquid conductor or *vice versâ*. Now this must always happen when a galvanic cell is used as the source of the current, for, as we have already seen, a compound liquid is one of the *essential* parts of such a cell. The laws of the chemical action of the current will be more minutely considered in the next section under the head of "electrolysis." For our present purpose we may broadly state that where the current *enters* the liquid the product of the decomposition of the liquid is either *oxygen*, or *chlorine*, or some element or radical which easily attacks such metals as zinc, lead, &c., and that where the current *leaves* the liquid *hydrogen*[1] or some *metallic* element is separated from the liquid. Now we have already seen (page 39) that the direction of the current *inside* the typical cell (Fig. 9) is from zinc to copper, or from the metal most easily attacked by the liquid to the metal less easily attacked. In all the cells we have hitherto described, the action of the current is therefore such as to produce oxygen at the zinc end of the cell, which dissolves or burns the zinc, and thus supplies the energy with which the current is endowed. But at the copper end the current, at every point where it leaves the liquid, separates out hydrogen, and as hydrogen does not combine with copper, it adheres to the plate in bubbles, which are at first very minute, but increase in size as the action continues. These bubbles of hydrogen cut down the current in two ways. In the *first* place they are very bad conductors of electricity, and act as a highly resisting shield which prevents the current passing easily from the liquid to the copper, and thus they materially increase the internal resistance of the cell. In the *second* place, hydrogen is an oxidisable metal, and therefore, as already pointed out, wherever a hydrogen bubble is in contact with the oxidising liquid there is a tendency for a current to flow from the hydrogen into the liquid, when a complete circuit is provided. But the electro-motive force thus set up is opposed to the electro-motive force at the zinc-acid junction, and therefore the effective electro-motive force or electric pressure of the cell or the complete circuit is only the difference between the zinc-acid electro-motive force and this hydrogen-acid electro-motive force. It is as if we had another electrical pump at the hydrogen-acid junction working against the electrical pump at the zinc-acid junction, and trying to pump the electricity round the circuit in the opposite direction. It is true that before the hydrogen bubbles formed there was a back electric pressure at the copper-acid junction, due to the fact that copper is oxidisable as well as zinc, but the copper-acid electric pressure is much less than the hydrogen-acid electric pressure, and therefore the formation of the hydrogen bubbles is a great disadvantage.

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[1] It should be noticed that hydrogen, though a gas, is regarded by chemists as a *metal*.

It will conduce to clearness if we here give a table, obtained from direct experiments, of the heat-value in "calories" of the oxidation of the various elements. The first column contains the name of the element; the second column the weight of the element in grams which must be oxidised to produce the number of calories given in the third column. The reasons for taking these particular weights will be considered in the next section (page 303). It may be stated, however, that they are the *relative* weights which enter into the chemical changes with which we are dealing. The last column contains the electro-motive force or electric pressure which, whenever the element is immersed in an oxidising medium, acts from the element to the medium. These electro-motive forces are calculated from the heat values by a method first pointed out by Sir William Thomson.

Table I.—Heats of Oxidation and Electric Pressures of Various Metals in Oxidising Media. O = 16

Metal.	Weight Oxidized.	Heat of Oxidation in Calories.	Electric Pressures in an Oxidizing Medium.
Magnesium ...	24 grams	143,900	3·13 volts
Potassium ...	78 ,,	139,600	3·03 ,,
Sodium... ...	46 ,,	135,600	2·95 ,,
Calcium ...	40 ,,	131,000	2·85 ,,
Zinc	65·5 ,,	85,800	1·86 ,,
Tin	59 ,,	72,650	1·58 ,,
Hydrogen ...	2 ,,	68,400	1·56 ,,
Iron	56 ,,	68,240	1·48 ,,
Lead	207 ,,	50,300	1·09 ,,
Copper... ...	63 ,,	37,200	·81 ,,
Mercury ...	200 ,,	20,700	·45 ,,
Silver	216 ,,	5,900	·13 ,,

The above table gives only the "heat of oxidation" of the various elements selected, and this necessarily falls short, as already pointed out, of the heat developed by the whole of the chemical action that takes place in a voltaic cell. For instance, in Wollaston's cell the zinc is converted not into zinc oxide, but into zinc oxide sulphated, *i.e.*, into sulphate of zinc, and to the heat of oxidation should be added the subsequent heat of sulphation. In order, therefore, to furnish fuller numerical data applicable to cells in which sulphuric acid is used as one of the exciting liquids, we append another table on the "heats of sulphation" of some of the metallic elements. It must be clearly understood that the numbers given in the column headed "Calories" are the results of purely *thermal* experiments, and that the Electric Pressures in the next column are *calculated* from these according to principles, the discussion of which would lead us beyond the limits of the plan of this book.

TABLE II.—HEATS[1] OF SULPHATION AND ELECTRIC PRESSURES OF VARIOUS METALS IN SULPHATING MEDIA.

Metal.	Weight Sulphated.	Heat of Sulphation in Calories.	Electric Pressures in a Sulphating Medium.
Potassium ...	78 grams	234,900	5·10 volts
Sodium ...	46 ,,	225,700	4·90 ,,
Calcium ...	40 ,,	219,800	4·78 ,,
Magnesium ...	24 ,,	219,300	4·76 ,,
Zinc	65·5 ,,	145,200	3·16 ,,
Iron	56 ,,	132,300	2·88 ,,
Cobalt	59 ,,	127,200	2·76 ,,
Nickel	59 ,,	126,100	2·74 ,,
Lead	207 ,,	112,900	2·45 ,,
Hydrogen ...	2 ,,	107,600 (sulphuric acid)	2·34 ,,
Copper... ...	63 ,,	95,100	2·07 ,,
Silver	216 ,,	59,500	1·29 ,,

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[1] The heats given are those of aqueous solutions of the various salts (except in the case of lead sulphate), but do not include the heat of formation of SO_3 (=103,300 calories).

Whilst dealing with these numerical data it would, perhaps, be well to give here, for convenience of reference, the "heats of formation" of chlorides with the corresponding electric pressures in chloridizing media. These are necessary in addition to the foregoing, because in some well-known batteries, notably the Leclanché (page 61), the zinc is converted into zinc chloride instead of zinc sulphate. The following numbers refer to such batteries:—

TABLE III.—HEATS OF CHLORIDATION AND ELECTRIC PRESSURES OF VARIOUS METALS IN CHLORIDIZING MEDIA.

Metal.	Weight Chloridized.	Heat of Chloridation in Calories.	Electric Pressures in a Chloridizing Medium.
Potassium ...	78 grams	199,800	4·34 volts
Sodium ...	46 ,,	192,800	4·19 ,,
Calcium ...	40 ,,	187,200	4·07 ,,
Magnesium ...	24 ,,	186,900	4·06 ,,
Aluminium ...	18 ,,	158,500	3·44 ,,
Zinc	65·5 ,,	112,800	2·45 ,,
Iron	56 ,,	100,000	2·17 ,,
Cobalt	59 ,,	94,800	2·06 ,,
Nickel	59 ,,	93,700	2·04 ,,
Tin	118 ,,	81,100	1·76 ,,
Hydrogen ...	2 ,,	78 600	1·71 ,,
Lead	207 ,,	76,000	1·65 ,,
Copper... ...	63 ,,	62,700	1·36 ,,
Silver	216 ,,	58,800	1·28 ,,
Mercury ...	200 ,,	49,900	1·08 ,,

A very slight examination of these tables will suffice to show how it is that the effective electric pressure produced by a Wollaston's cell (Fig. 7) is diminished by the deposition of hydrogen bubbles. When the cell is new, and the zinc and copper both clean, the tendency of the zinc to oxidise gives an electric pressure of 1·86 volts, acting from the metal to the liquid, and the tendency of the copper to oxidise gives an electric pressure of 0·81 volts, acting from the copper to the liquid. In the completed circuit these pressures oppose one another and produce an "effective" pressure of 1·05 (*i.e.*, 1·86—0·81) volts available for driving electricity round the circuit. But if the copper be replaced by hydrogen, the electric pressure at the hydrogen-liquid junction is 1·56 volts, and thus if the immersed part of the copper plate becomes completely covered with hydrogen, the effective electric pressure in the circuit will fall to 0·30 (1·86—1·56) volts, or about one-seventh of its previous value. These figures are taken from the table of the heats of "oxidation"; if we employ instead the pressures corresponding to the heats of "sulphation," we find that the effective pressure of the unpolarised cell is 1·09 (*i.e.*, 3·16—2·07) volts, which falls on polarisation to 0·82 (3·16—2·34) volts.

The tables are further useful as a guide regarding the probable effect upon the electro-motive force of the cell of substituting other metals in the place of the zinc or the copper. Thus, if the zinc be replaced by a plate of metallic magnesium, the electro-motive force of the magnesium-acid-copper combination would be approximately 4·76—2·06=2·70 volts, a much higher value than when zinc is used. Unfortunately, as anyone who has used the magnesium light knows, magnesium is an expensive metal, costing about sixty times as much as zinc. If it could be produced at a price approaching that of zinc, it would be largely used in voltaic batteries, and these might then be made to compare more favourably with other methods of producing the electric current, though "local action" would probably be troublesome. Any pair of metals in the tables placed in a liquid of the nature referred to in the particular table will form a simple voltaic cell, and the electro-motive force in volts that the combination will give can be approximately foretold by taking the difference of the numbers in the last column corresponding to the two metals selected. The fundamental conditions necessary for the formation of a simple voltaic cell may be defined to be the presence of at least one junction of a solid and a liquid at which chemical action can take place; there will of necessity be another junction of a solid and a liquid when the circuit is completed, and if chemical action, or even chemical strain, is possible at this junction also, it is essential that its energy value should differ from the energy value of the chemical action at the first junction. These conditions are usually fulfilled by placing two plates of dissimilar metals in a liquid or in two different liquids separated by a porous diaphragm, but they can also be satisfied by putting two plates of the same metal into two different liquids that are in conducting communication with one another, provided that the chemical action of one liquid on the metal is different from that of the other. Such a cell was devised by Napoleon III.

Modern Primary Batteries.

The methods by which polarisation has been reduced in modern batteries may be divided into three classes, viz. :—

(*a*) Mechanical methods.
(*b*) Chemical methods.
(*c*) Electro-chemical methods.

In the first of these the polarising films are removed from the negative plate mechanically, either by brushing the plate, or by agitating the liquid, or by using some kind of mechanical disturbance. In the second, the liquid that surrounds the negative plate contains some chemical body which is capable of combining with the polarisation bubbles as they are formed, and thus, as it were, strangling the polarisation at its birth. In the last class of methods the metal that is separated out of the liquid at the negative plate is in a solid form, and is usually the metal of which the negative plate itself is composed, so that the deposition of fresh metal on the plate does not alter the chemical constitution of the battery.

We shall now proceed to describe some of the batteries in which attempts, more or less successful, have been made to diminish polarisation; the particular method adopted will be pointed out in each case.

The Daniell Battery and its Modifications.

The first successful attempt to correct the evils of polarisation was made by Professor Daniell in 1836. The Daniell cell, one type of which is illustrated in Fig. 10, consists of a zinc plate dipping into either dilute sulphuric acid or zinc sulphate, and a copper plate in a solution of copper sulphate or blue vitriol. The two liquids were in the original cell separated by a porous partition of unglazed earthenware, but in some of the special modifications of the cell this partition is removed, and the difference of the

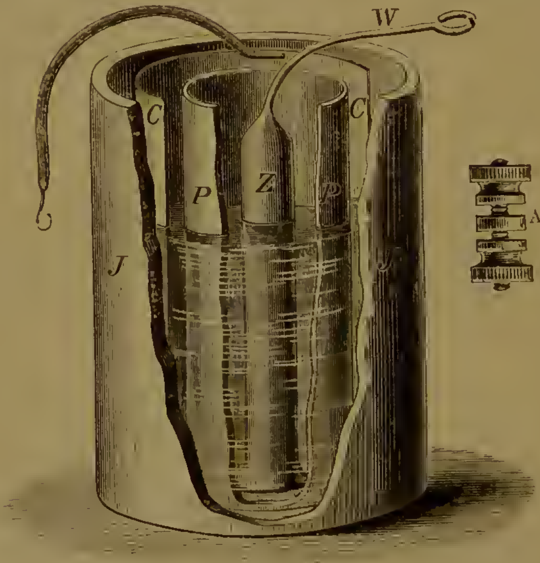

Fig. 10.—Daniell's Cell.

densities of the liquids is relied upon to keep them from mixing. The original form of the cell differed from that shown in Fig. 10 in having the containing vessel made of copper, which formed the negative plate; this method of making the containing vessel one pole of the battery is possible, because when the cell is working fresh copper is continually deposited on the copper plate, which thus gradually grows thicker and does not waste away. The cheapness with which glass and other containing vessels can be produced has caused the device to be generally abandoned, though from time to time a new battery makes its appearance with its outer vessel forming the negative plate. In Fig. 10 C is the copper plate dipping into a solution of copper sulphate contained in the stoneware jar, J, and Z is a thick, heavy rod of zinc in a solution of dilute sulphuric acid or of zinc sulphate contained in a "porous pot" or vessel, P, of unglazed earthenware. W is a copper wire round one end of which the zinc rod has been cast, and it forms one pole, the negative pole, of the battery. The external junction of W and Z should always be high enough up to be quite out of the reach of the liquid in the porous pot, P. A convenient clamp to use for making external connections is shown at A.

When this cell is working, the *chemical action* is a comparatively simple one. The copper sulphate ($CuSO_4$) is decomposed in the outer vessel, and solid copper is deposited on the copper plate. The compound radical sulphion (SO_4) set free attacks a neighbouring molecule of copper sulphate, seizing the copper and liberating another molecule of sulphion which attacks an adjacent molecule of copper sulphate, and so on until the sulphuric acid is reached. This in its turn is attacked by sulphion, and the action proceeds right up to the zinc plate, from which the last link of sulphion in the chain of molecules that are changing partners seizes an atom of metallic zinc and forms zinc sulphate. The above actions must be regarded as taking place simultaneously all along the line. The net result is that copper is deposited on the copper plate, and zinc is dissolved off the zinc plate; the zinc sulphate in the sulphuric acid becomes more concentrated, and the solution of copper sulphate is impoverished. To keep the latter solution up to its full strength some crystals of copper sulphate should be placed at the bottom of the outer vessel, or, better still, put on a little perforated shelf just below the level of the top of the liquid.

The E.M.F. of a Daniell's cell is found to vary from 1·07 volts to 1·14 volts, according to the densities of the solutions of copper sulphate and zinc sulphate. A reference to Table II., page 46, will show that the difference between the heats of sulphation of zinc and copper is equivalent to an electric pressure of 1·09 volts, a value which lies between the limits just named. Increase of the density of the zinc sulphate solution slightly diminishes the E.M.F. of the cell whilst an increase of the density of the copper sulphate solution slightly raises it. The E.M.F. remains very constant whilst the battery is working, for unless the copper sulphate becomes too weak there can be little or no polarisation, since solid copper is deposited on the copper plate and the chemical constitution of the battery remains unchanged. This cell is therefore one in which an *electro-chemical method* is adopted to get rid of polarisation. Should the copper sulphate solution become too dilute, the water may be decomposed and hydrogen deposited on the copper plate; hence the necessity for having a supply of crystals of copper sulphate in the solution.

The internal resistance of the cell depends very largely upon the resistance of the porous pot; it seems to be impossible to manufacture these pots of uniform resistance, pots made from the same materials and baked at the same time showing large variations in their resistance. The resistance of a pot 7 inches high and about 2½ inches wide of the type shown in Fig. 10, may vary from ⅓ to 1·5 ohms. In the cells used by the Post Office the resistance is about 2·5 ohms.

Modified Daniell's Cells without a Porous Diaphragm.—Many modifications of the Daniell's cell have been devised in which the internal resistance is reduced by dispensing with the porous diaphragm. As already mentioned, the difference in the densities of the zinc and copper sulphates are relied upon to keep the copper sulphate from reaching the zinc plate, but this device is accompanied with the drawback that the cell must not be roughly moved about or the liquids will be mechanically mixed. One of these modifications is the Lockwood cell shown in Fig. 11. In this cell the zinc plate, Z, is shaped somewhat like a heavy wheel with thick spokes and rim, and is suspended from the top of the vessel by the three arms, *a a a*; it is surrounded with a solution of zinc sulphate. The copper plate consists of two spirals of stout copper wire; one of these is seen at S, and the other lies on the bottom of the cell. These plates are connected by a copper wire, and between them are crystals of copper sulphate; from the upper one a copper wire insulated with gutta-percha is led up through the liquid to form the external positive electrode, C. The cell is about 11 inches high and 5½ inches wide.

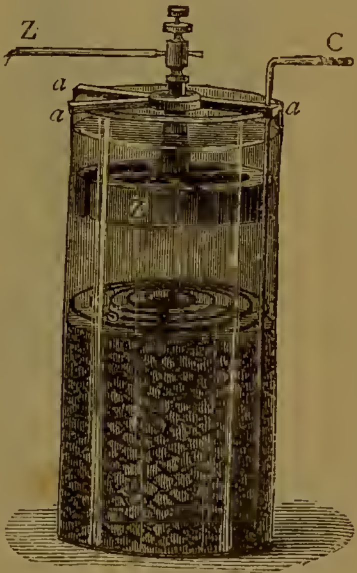

Fig. 11.—The Lockwood Cell.

In the Meidinger cell, shown in Fig. 12, the copper plate also consists of a spiral of copper wire, S, but this is put at the bottom of a smaller glass vessel placed inside the outer containing vessel of the cell. Into the mouth of this tumbler the neck of an inverted flask, F, is inserted, and this flask is filled with crystals of copper sulphate. The zinc plate, Z, which is cylindric, rests upon a shelf formed by making the lower part of the outer vessel of smaller diameter than the upper part. An insulated wire, C, is brought up from the copper spiral and forms the positive pole of the cell, whilst a similar wire, Z′, attached to the zinc cylinder above the level of the liquid, is the negative terminal or pole.

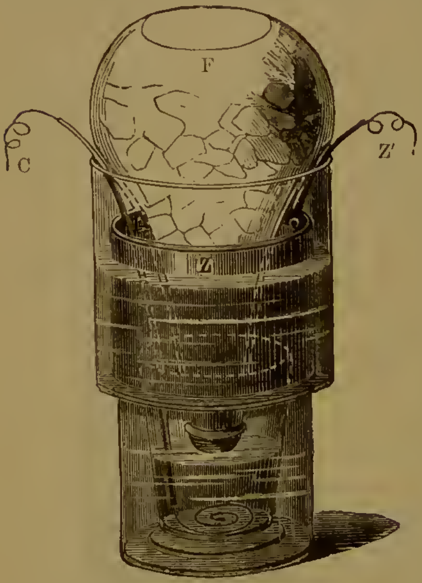

Fig. 12.—The Meidinger Cell.

The last modification we shall describe here is the Calland cell, which was developed from the Meidinger in 1861. In this cell the cylindric zinc plate either hangs from the upper edge of the outer vessel, as shown in Fig. 13, or rests upon a shelf as in the Meidinger. The copper plate is either a spiral of sheet copper or a short copper cylinder placed

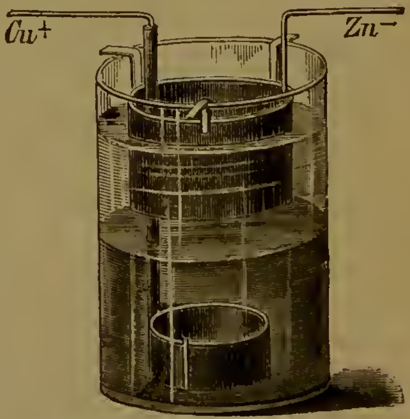

Fig. 13.—The Calland Cell.

at the bottom of the cell as shown. Copper sulphate is poured into the cell to within about 1½ inches of the zinc plate, and the vessel is then carefully filled to a convenient height with either water or zinc sulphate. The figure shows clearly the relative quantities of the two liquids. From time to time the zinc is cleaned and fresh copper sulphate added These last cells are much used in France for Telegraphy.

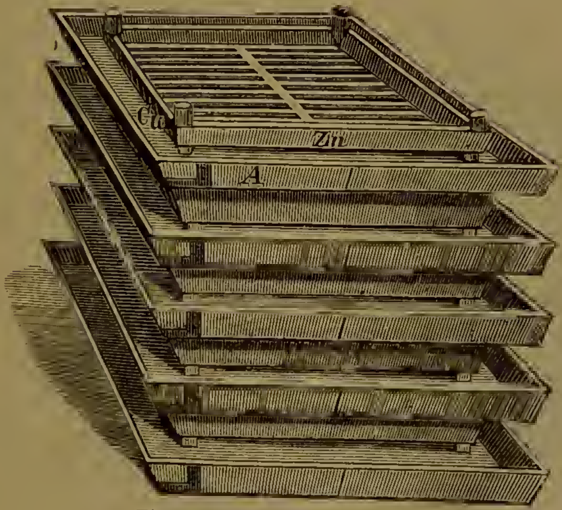

Fig. 14.—The Kelvin Battery.

Modified Daniell's with Porous Partitions.—Many materials have been used for the porous partitions of Daniell's cells; amongst these may be mentioned parchment, sawdust, sand, &c. In Lord Kelvin's tray battery, five cells of which are shown in Fig. 14, the zinc plate, Zn, which is in the form of a heavy grid of metal, is covered on its lower side with parchment, which forms the porous partition. This grid and its parchment covering rest upon four wooden blocks in a shallow wooden tray, A, the bottom of which is lined in the inside with sheet lead, which is soon coated with copper by the action of the current. This wooden tray rests upon blocks supported by the zinc of the cell below, and thus the battery is built up, the zinc of each cell being connected by straps of lead to the lead lining of the wooden tray above it. The cells have to be set up where they are to be used, as they are obviously not portable without taking to pieces. They must be carefully levelled so that when the liquids are poured in they cover the plates evenly. Water or a zinc sulphate solution is poured into the parchments surrounding the zincs, and copper sulphate is poured into the outer trays. On account of the large surfaces of the plates, the internal resistance of this form of Daniell's cell is low, and it is capable of giving a fairly steady current for a considerable time. It was used in cable telegraphy for driving the electro-magnetic motor of some early forms of the syphon recorder.

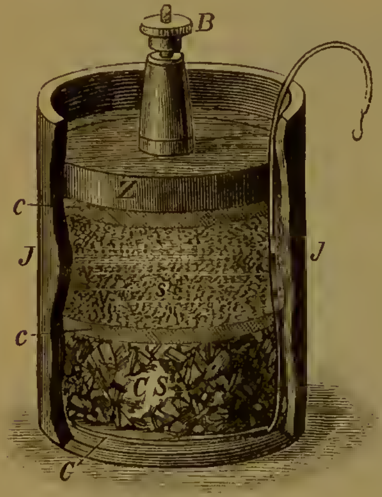

Fig. 15.—Minotto's Cell.

A modification of the Daniell's cell, very useful where the battery has to be moved about, or where it has to be left for long intervals without attention, is Minotto's Cell (Fig. 15). In this cell the porous diaphragm of the ordinary Daniell is replaced by sand or sawdust. C is the copper plate which lies at the bottom of the cell, and has attached to it a flat strap or a wire of copper covered with gutta-percha and led up through the cell to the outside, where it is the positive pole. On the top of this copper plate is a thick layer, CS, of crystals of copper sulphate, which are separated from the sand or sawdust that lies above them by the thin canvas sheet, *c*. On the top of this sand or sawdust is placed another thin canvas sheet, *c*, on which rests the heavy zinc plate, Z, cast with a column of zinc rising from its centre, to the top of which is attached the brass binding screw, B. Before the sand or sawdust is put in, it should be damped with solution of zinc sulphate, and after the cell has been made up as above described, additional zinc sulphate solution is poured in until it just covers the flat part of the zinc plate. Sand is most suitable for stationary cells, and sawdust for those which have to be moved about. This cell is used for Telegraphy in India.

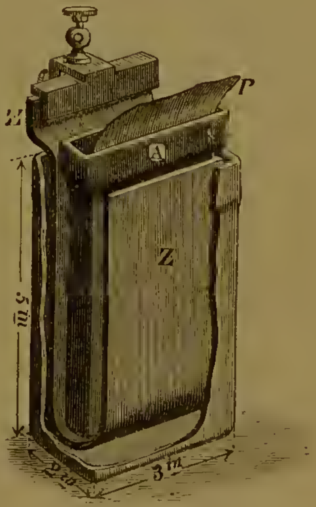

Fig. 16.—Grove's Cell.

Another form of Daniell's cell will be described when we are discussing cells suitable for standards of E.M.F. (*see* page 405).

Nitric Acid Batteries.

In these batteries polarisation is prevented by surrounding the negative element of the cell with strong nitric acid, which is a powerful oxidiser. Consequently, when the battery is working, the hydrogen which otherwise would be deposited on the negative plate is oxidised, and forms water. The two best known and most used batteries of this type are Grove's and Bunsen's.

Grove's Cell.—A modern and compact form of this cell is shown in Fig. 16. The zinc plate, Z, is bent into a U shape, and a narrow porous pot, A, rests in the bend of the U; inside the porous pot is a thin *platinum* plate, P, surrounded by *strong nitric acid*. This plate is the negative element, and thus replaces the copper of the Daniell's cell.

The outer vessel is frequently made of thin ebonite, which is much lighter than glazed earthenware; it contains the solution of dilute sulphuric acid, in which the positive zinc plate is immersed. The advantages of this cell are that it has a *high E.M.F.* of about 1·93 volts, and a *low internal resistance*, which, in a cell having the form and dimensions shown in the figure, may be as small as 0·15 ohm. A battery of these cells is therefore capable of producing a powerful current, and such batteries were much used, before the dynamo was developed, for producing the electric arc-light, especially for lecture purposes. As the battery works, however, the current falls off, both because of the weakening of the nitric acid and the replacement of sulphuric acid by zinc sulphate. The price of the platinum plates, moreover, makes the first cost heavy. The action of the cell is that of the ordinary voltaic couple already explained, with the exception, however, that the polarising hydrogen is oxidised by the nitric acid. Hence arises the greatest disadvantage of the cell; in oxidising the hydrogen the nitric acid is decomposed, and poisonous nitrous fumes are evolved. A Grove's battery should therefore always be placed either in the open air, or in a cupboard connected with a flue or shaft in which there is a strong exhaust draught.

Bunsen's Cell.—Bunsen reduced the prime cost of the Grove's cell by replacing the expensive platinum by a block of hard gas-coke or carbon, but the compactness of the cell suffered by the change. Fig. 17 shows the usual form of this cell. The cylindric zinc plate, Zn, and the dilute sulphuric acid, are contained in the outer vessel, and the carbon block, C, with the strong nitric acid, is inside the porous pot. A difficulty is sometimes experienced in getting good contact with the carbon block, but this should be accomplished with the clamp shown in the figure. The clamp which is shown attached to the zinc is for the purpose of joining it to the carbon of the next cell in putting together a battery. A somewhat different kind of clamp for the carbon is shown at A, and the corresponding one for the zinc at B. These are drawn to a larger scale; with them the connections from cell to cell can be made with ordinary wire. The chemical action of the cell is the same as that of the Grove's cell, but the E.M.F. is a little less, and the resistance is greater. It thus possesses all the disadvantages of the Grove's cell, without the corresponding advantages to the same degree.

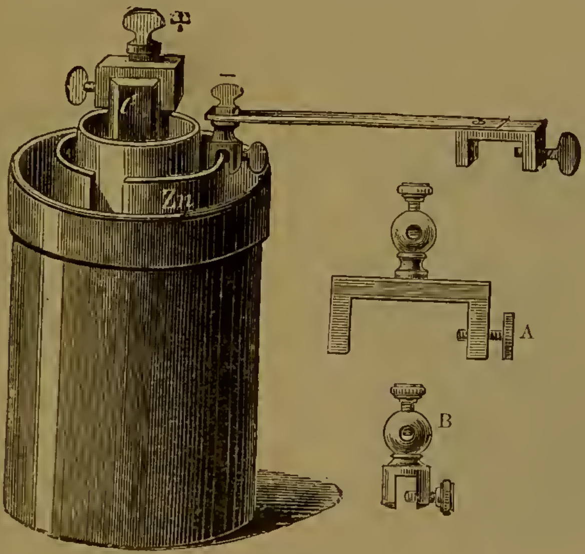

Fig. 17.—Bunsen's Cell.

Bichromate or Chromic Acid Batteries.

The inconveniences arising from the nitrous fumes given off when nitric acid is used as an oxidiser, are avoided by substituting either bichromate of potash or chromic acid. So convenient has the former of these liquids proved to be for this purpose that numerous batteries have been invented, only differing from one another in the proportions of bichromate of potash in the depolarising solution and in the addition sometimes of other materials. For ordinary working the bichromate solution may be made as follows :—Carefully and slowly add half a pint of strong sulphuric acid to nine ounces of well-powdered crystals of potassium bichromate ; when the reaction is complete and the mass has cooled down add slowly $5\frac{1}{2}$ pints of water. The water will dissolve all the solid matter, and the final product will be a richly coloured acid solution of potassium bichromate.

In all the usual forms of bichromate cells the positive and negative plates are of zinc and carbon respectively. These are sometimes contained in a single vessel, as in the well-known "bottle" form of cell seen in Fig. 18. The zinc plate, Z, is attached to a brass rod, *a*, which slides in a collar ; this collar is connected by a strip of brass on the ebonite cover to the binding screw, A, which is the negative terminal of the cell. Two flat strips of carbon, K K, are placed one on either side of Z, and are connected with one another and the other binding screw, B, which is therefore the positive terminal. The solution used is that just described, but as this solution acts upon the zinc when the battery is idle, it is necessary at such times to raise the zinc plate by the rod, *a*, until it is clear of the liquid. A clamping screw on the collar enables it to be fixed in the raised position.

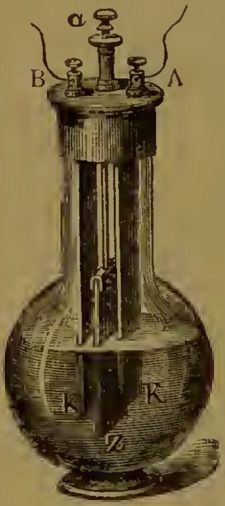

Fig. 18.—The Grenet or Bottle Bichromate Cell.

In order to avoid the necessity of raising the zinc plate out of the liquid when the cell is not in use, a porous pot is frequently employed to contain the zinc as seen in Fig. 19, which represents Fuller's modification of the bichromate cell.

The zinc, Z, is a solid block of metal cast on to a well-amalgamated copper rod; this stands in a porous jar, at the bottom of which is placed a small quantity of mercury, which keeps the zinc well amalgamated. The liquid in the porous jar is usually dilute sulphuric acid, but a solution of common table salt is sometimes employed instead. In the latter case the dissolution of the zinc gives zinc chloride instead of zinc sulphate. The outer vessel contains the carbon plate, *a*, dipping into an ordinary bichromate solution.

The E.M.F. of a bichromate cell is higher than that of a Grove's or Bunsen's, being a little above 2 volts, and this E.M.F. is fairly steady when only small currents are taken from the battery. If, however, large currents are used, the E.M.F. falls off somewhat rapidly, but recovers itself after a period of rest. The resistance of the bottle form is small, because of the absence of the porous pot, but the resistance of Fuller's and similar forms is about the same as that of a Bunsen's cell of the same size.

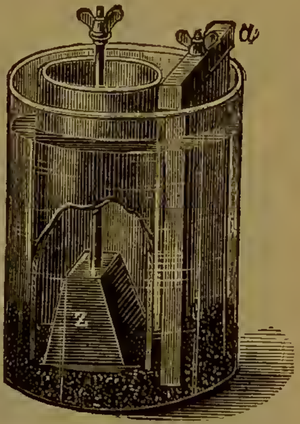

Fig. 19.—Fuller's Bichromate Cell.

When the bichromate solution becomes exhausted, its colour changes from a rich orange to a deep blue, and as soon as this change is observed, the solution should be renewed.

The Leclanché Cell.

In this cell, which is perhaps more widely used than any other for most ordinary purposes, with the exception of telegraphy, the chemical method of preventing polarisation is employed, but the mineral pyrolusite, *i.e.*, manganese dioxide, is the oxidiser, instead of nitric acid or bichromate of potash. This mineral readily parts with some of its oxygen, being reduced to a lower oxide of manganese.

The cell is illustrated in Fig. 20, and consists of an outer square or rectangular glass vessel with an indentation in the neck at A for the reception of the positive element, a zinc rod, Z. The negative element, a carbon plate, C, stands in a porous pot, in which the remaining space is packed up tightly with a mixture of small pieces of gas-coke and manganese dioxide. The function of the porous pot in this case is not to separate two liquids, but merely to afford a mechanical support to the above mixture. There is only one liquid used in the cell—namely, a saturated solution of sal-ammoniac (chloride of ammonium), which is placed in the outer vessel, and slowly percolates through the porous pot. The latter is closed at the top with pitch, in which a small hole is left so that a little water, or sal-ammoniac solution, may be poured in to increase the initial conductivity and start the action of the cell. The upper part of the carbon plate is well soaked in paraffin-wax, and has a lead cap cast upon it, to which connection is made by means of the terminal screw shown.

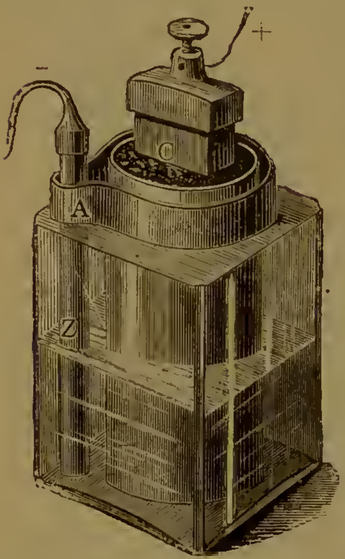

Fig. 20.—The Leclanché Cell.

When the cell is working, the zinc is dissolved, forming zinc chloride, and ammonia gas is set free; the polarising hydrogen, which would otherwise be deposited on the carbon plate, is oxidised by the manganese dioxide forming water, the dioxide being reduced by the loss of oxygen to manganese sesquioxide. The E.M.F. is 1·47 volts, but falls off rapidly when the cell is used to send a current; it, however, very quickly recovers when the cell is standing idle, and it is this quick recovery, combined with the absence of noxious fumes, and the small amount of attention required, that makes the cell so useful for intermittent purposes, such as the ringing of electric bells. The internal resistance is from 4 to 10 ohms.

To diminish the resistance introduced by the use of the porous pot Leclanché invented a form of negative element and depolariser combined, in which the stiffness which would enable the latter to stand without support is procured in the following way. The mixture of gas-coke and pyrolusite is impregnated with gum and kept for some time at the temperature of boiling water, whilst subjected to a pressure of about 4,000 lbs. on the square inch. A little potassium hydrogen sulphate (bisulphate of potash) is also diffused through the mixture, and is found to assist the solution of the zinc salts. In this way a hard, compact mass of depolarising material is produced, which can be strapped to the carbon plate with indiarubber bands, as seen in Fig. 21, where *a a* are the depolarising plates. This form is known as the Agglomerate Leclanché. The zinc rod in the modification figured is held in position by the same rubber straps that bind the plates, *a a*, to the carbon, and is kept from coming into contact with these plates by a block of wood. The resistance of such a cell is much less than the ordinary Leclanché, but the agglomerate plates slowly disintegrate.

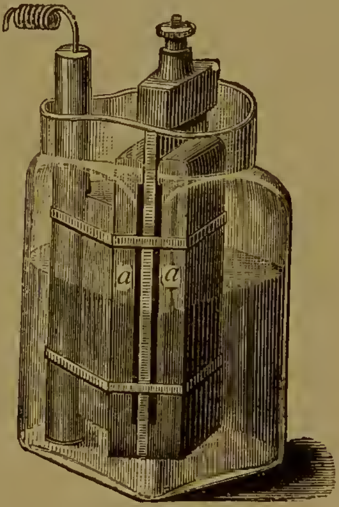

Fig. 21.—The Agglomerate Leclanché Cell.

Various other modifications of this cell have appeared from time to time, but the original porous pot form of Fig. 18 is still largely used. Three different sizes (Nos. 1, 2, and 3), varying in height from 4½ to 6 inches, are usually manufactured.

Primary Batteries for Electric Lighting.

The employment of primary batteries for the production of the electric light offers the great advantage, that their use dispenses with the noise and dirt which accompany the employment of steam or gas engines and dynamos, and that their supervision, when properly planned, does not call for the constant attention required by moving machinery. There is, however, the great drawback that the fuel used is expensive, for in all practical primary batteries hitherto devised, the energy of the current is derived from the oxidation of zinc, in exactly the same way as in the batteries we have just described. Attempts have been made from time to time to use cheaper metals such as iron, but the use of the latter introduces further disadvantages which are not present in zinc cells. On the other hand, when a dynamo machine is used to generate an electric current, the energy, as we shall see later on, is primarily obtained either from the combustion of coal, coal-gas, or petroleum, and transmitted to the dynamo through the medium of an engine, or from a stream of water whose energy is transmitted to the dynamo by a turbine or water-wheel. Leaving the latter case out of consideration for the present, as being somewhat less common, we have to compare the cost of energy derived from burning zinc with that derived from burning carbon in some one or other of its forms. Now the cost of 1 lb. of zinc may be taken as 2½d., whilst 1 lb. of coal at 12s. 6d. per ton only costs 0·07d., and thus the prime cost of zinc is about 35 times that of coal. Then, again, 1 lb. of zinc only yields by oxidation about ⅙th of the energy that carbon yields on complete oxidation. This makes the energy derived from zinc about 210 times as costly as that derived from coal. On the other hand, a steam boiler and engine are exceedingly wasteful means of transforming energy, much of the energy obtained from the combustion of the fuel escaping up the chimney and in other ways. If we suppose that about 8 per cent. of the energy of the coal is eventually converted into electric energy by the dynamo, the relative cost of zinc and coal is reduced to about 17 to 1, assuming that all the energy of the zinc is usefully available, which is not the case, because of the unavoidable internal resistance of the battery. The above argument deals only with one aspect of the question, and does not take into account the greater cost of attendance, and probably greater first cost in the case of the boiler, steam engine, and dynamo. There is also the further consideration, much relied upon by a certain class of inventors, that the final products from a primary battery consist of materials that still have a market value. Up to the present, however, no scheme has been tried upon a large scale in which these products have been systematically collected and placed upon the market, and it seems more than probable that the cost of collection and treatment would be so great as to render any profit from this source almost, if not quite, a vanishing quantity.

Electrically, the drawbacks of a primary battery that is required to furnish a heavy current are the low E.M.F. and large internal resistance of the individual cells. The former, which, as we have already seen, cannot much exceed 2 volts, renders it necessary to employ a fairly large number of cells in order to bring up the electric pressure to that required for the glow or arc lamps in ordinary use. The internal resistance has practically the same effect in diminishing the available pressure, as part of the total E.M.F. has to be employed in driving the current through this internal resistance, thus reducing the external pressure, and rendering still more cells necessary to bring up that pressure to the required value. Another evil caused by internal resistance is the varying external pressure of the battery for different currents, because with small currents the effect of the internal resistance is less marked than with large currents. We shall return to this point again (*see* page 289).

Other drawbacks connected with primary batteries are those incidental to the use of corrosive liquids, the necessity for specially trained attendants, and the annoyance caused by noxious fumes ; but these, and some other minor matters, are not necessarily inherent in the method, and may be and have been more or less successfully overcome by careful design and attention to details.

With the above disadvantages, both fundamental and accidental, against them, it is not surprising that primary batteries have not as yet been extensively employed for illuminating and other purposes which require heavy currents. Still, there are cases in which, even at a somewhat enhanced cost, the primary battery may be preferred, with its quietness and cleanliness, to its noisier, dirtier, and cheaper rival. Innumerable inventors have done their best for it, the favourite form being some modification of the bichromate battery. But no battery has, up to the present, attained such a measure of success in this direction as to justify us in devoting space to a description of it.

Secondary Batteries or Accumulators.

In dealing with the chemical production of the current by primary batteries we have frequently had to refer to the evil effects of the polarisation of the plates of the cells when currents are generated, and much of our space was occupied with descriptions of various devices for overcoming the evil. We pointed out that the trouble was due to a fundamental property of the electric current, namely, that whenever it passed from a solid to a liquid electrolytic conductor, or *vice versâ*, the liquid was decomposed. The products of decomposition either adhere to or remain in the neighbourhood of the incoming and outgoing conductors, and, especially in the case of the latter, oppose the passage of the current by setting up a counter or back electro-motive force. In the case of a primary battery this back electro-motive force is so much deducted from the total available electro-motive force of the current generator. But the incoming and outgoing conductors, technically called the *electrodes*, may be plates of similar material dipping into the liquid conductor. In this case the arrangement before a current is passed through it does not fulfil the conditions (*see* page 49) necessary to constitute a primary battery, for there is no resultant E.M.F. in the combination. But if, owing to the above-mentioned property of the current, the products of decomposition are such as to alter the character of the surfaces exposed by the electrodes to the liquid, then, when the current is stopped, this altered condition of the electrodes may persist for a longer or shorter interval. During this time the apparatus will be similar to a primary battery, in that it will consist of two *different* conducting surfaces immersed in a liquid that can act chemically upon them. These surfaces will be at different potentials just as in an ordinary cell, and the arrangement will possess a resultant E.M.F. due to the polarisation. If now the electrodes be connected by an *external* conductor, a current will pass through this conductor. Obviously the E.M.F. of polarisation must be in such a direction as to tend to stop the current which produced it, or in other words, tend to drive a current in the reverse direction. Therefore when this E.M.F. of polarisation is itself used to generate a current, that current must pass through the *liquid* in the opposite direction to the original current, and the current will last until the electrodes are restored to their original condition by the using up of the available products of polarisation.

As an illustration of the point under consideration, the following experiment may be made. AA (Fig. 22) are two Bunsen or bichromate cells, joined up as shown. The positive pole, C, of the battery is connected to one terminal of a galvanometer (*see* page 336), the other terminal of which is joined to P, one of two platinum plates, which dip into a vessel, V, of dilute sulphuric acid. The other plate, N, is connected to one end of a pivoted metallic tongue or switch, S, whose other end can be placed either on the stud *a* or on the stud *b*. The stud *a* is joined by a wire to the negative pole Z of the battery A, whilst the stud *b* is joined to some point, D, on the wire connecting C with the galvanometer. If now the switch, S, be placed on *a*, the current from the battery will flow round the circuit CDGPNS*a*Z in the direction indicated by the arrows *ppp*. The needle of the galvanometer G will be deflected in a certain direction, and in the vessel V oxygen gas will be liberated at the plate P, and hydrogen gas at the plate N. The greater part of these gases may escape into the air, but a

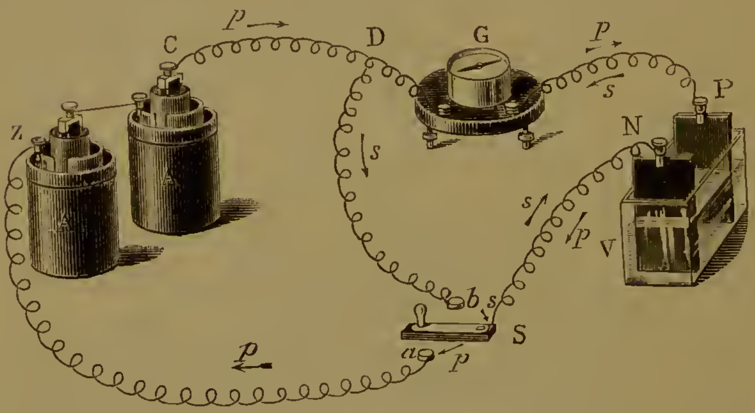

Fig. 22.—Experiment on Polarization.

close examination will show that the surfaces of the plates are covered with minute bubbles of gas. We therefore have in the vessel V no longer two clean platinum plates opposed to one another, but a plate of platinum coated with oxygen gas opposed to a plate of platinum coated with hydrogen gas. For these two plates thus modified the chemical affinity of the liquid is different. If now we move the switch S over to the contact *b*, we have a closed conducting circuit, PGD*b*SN, in which the vessel V and its contents are of the nature of a galvanic cell. The galvanometer G will be observed to indicate a current in the *opposite* direction to the previous current, *i.e.*, in the direction of the arrows *sss*. This current will rapidly die away and the galvanometer needle return to zero. When this happens an examination of the plates PN will show that all trace of gas has disappeared from them and that they are in their original condition. The vessel V and its contents in this experiment play the part of a *secondary cell* or *accumulator* as it is called; it was in the first instance *charged* by the battery A, with the *primary* current *ppp*, and on this battery being disconnected from it, it was able to give a brief *discharge* or *secondary* current *sss* through the galvanometer G.

There is another way of regarding the above experiment. We have already had occasion to draw attention to the fact that one of the greatest stores of energy at our disposal is the energy of chemical separation of materials that have a tendency to combine. Also that if this combination be allowed to take place the resulting products contain a less store of energy than the original materials. On the other hand, if we restore the constituents of these products to their original condition we endow them again with their original energy. But to do this we must supply energy to them, and the energy so supplied may be regarded as again stored up in the materials in the form of energy of chemical separation. Now in the experiment just described the oxygen and hydrogen gases that appear at the electrodes P and N possess a greater store of energy, by reason of their separation, than the water which was decomposed in their formation. This energy has been supplied to them through the agency of the electric current, from the energy given out by the battery A, and represents so much energy withdrawn from the current and rendered unavailable for other work, such as heating the conductors. As long as the gases remain adhering to the platinum plates the energy of such portions of the gases is, as it were, still under our control, and can be made available for sending a return current; it was so utilised in the experiment. The energy of the gases which become detached from the electrodes and escape into the open air passes out of our reach and is lost to us.

We have then, in the arrangement described, a method of storing up a part of the energy of the battery A, but a little consideration will show that it is not an economical or a useful one. It is uneconomical, because in the process we may lose a great part of the energy we wish to store by the escape of the gases from the plates. It is not of much use, because the total quantity of energy stored is not great, and moreover, if we allow a long interval to elapse between the breaking of the charging circuit and the closing of the discharging circuit, we shall find that a large portion even of this small amount of energy has been lost by still more of the gases becoming detached from the plates.

But the experiment illustrates a principle which, under other conditions, has been developed so as to provide us with a method of storing energy which is extremely useful and convenient, and at the same time fairly economical. It is at once evident, that for these results to be obtained the products of decomposition during charging must neither be gases nor soluble in the liquid contained in the vessel V; they will then more or less perfectly remain on the plates P and N as they are formed, and to the extent to which this condition is observed may we expect to find that the energy spent in the decomposition during the time of charging is available for supplying energy in the form of the electric current of discharge. Modern *secondary batteries* or so-called *accumulators* are simply arrangements, more or less perfect, for fulfilling the conditions thus briefly indicated, and a little consideration will show that these *storage batteries* do not store electricity, as is popularly supposed, but only energy of chemical separation in a form convenient for the production of an electric current. Before describing a few existing types of these batteries, a brief outline of the history of the subject may be interesting.

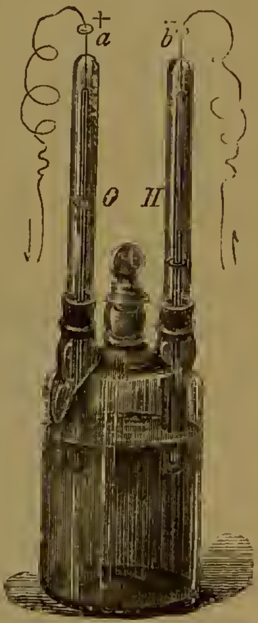

Fig. 23.—Grove's Gas Battery.

Historical Notes.—The fact that the electrodes used in the decomposition of water could give, on the cessation of the current, a current in the opposite direction, was observed early in the present century, and Ritter in 1803 constructed a secondary pile similar to Volta's pile (Fig. 5), but with the metal discs between the moistened cards all made of the same material. This pile was charged by being connected to a Volta's pile, and on breaking the charging circuit was able to give a small current. The amount of energy stored was extremely small.

The first application of the principle by which a moderate amount of energy was stored was in Grove's "Gas Battery" (Fig. 23), invented in 1839. Two long tubes, O and H, filled with acidulated water, are inverted in the stoppered flask; platinum wires *a* and *b* are sealed through the closed ends of the tubes. The wires are each attached inside the tubes to a long strip of platinised platinum, and outside they support two little mercury cups into which the conducting wires from a battery can be dipped. To charge the gas battery the wires of an ordinary galvanic battery of not less than two Bunsen's or Grove's cells are connected with the mercury cups, so as to send a current in the *opposite* direction to that indicated by the arrows. Oxygen gas is then liberated in O and hydrogen gas in H, these gases displacing the water in the tubes. A large amount of the gas liberated is absorbed by the prepared platinum plates, but eventually the H tube becomes filled with gaseous hydrogen, and the charging circuit should then be broken. The arrangement now consists essentially of plates of oxygen and hydrogen in acidulated water, and will behave like a galvanic cell. If the wires of a conducting circuit are connected to the mercury cups, a current will flow through that circuit in the direction of the arrows. During the flow of this current the gases will be gradually used up and the water will rise in the tubes; finally the water will again fill the tubes and the current will cease. It is perhaps interesting to notice in passing that the battery can be charged by forcing oxygen and hydrogen, generated by any of the well-known methods, into the tubes O and H. It will also generate a current when other gases are used, and Grove has given[1] a table in which various gases and vapours are arranged in a series according to the E.M.F. that they produce in his battery.

Grove's gas battery remained little more than a scientific curiosity, though extremely interesting from the point of view of theory, until Gaston Planté took up the subject in 1860, and in a series of extensive investigations led the way along the path which modern inventors have travelled in developing the secondary battery. As the result of many experiments, Planté found that the best metal to use for the electrodes was lead, which forms several oxides, and one of whose principal salts, lead sulphate, is insoluble in water and acids. In order to diminish as much as possible the internal resistance of his cell, Planté eventually adopted the same principle that had been employed by Hare in his Deflagrator (Fig. 8), that is, he used large sheets of metal for his positive and negative plates, and rolled these up into a compact form with insulating strips between them. Fig. 24 shows on the right the extended lead sheets, with the insulating strips, before being rolled up, and on the left is seen the compact cylinder formed by these after rolling. The sheets are 0·05 inch thick, and the insulating bands are of indiarubber $\frac{1}{5}$ inch thick, the projecting lugs that are to form the terminals of the cell being in one piece with the metal sheets. The cross at the top of the cylinder is of ebonite, and is for the purpose of keeping the plates in position. The cylinder is next introduced into an ebonite or glass vessel (Fig. 25) containing dilute sulphuric acid; the terminal lugs G and H, already referred to, are brought out and made fast to the brass pieces M_1 and M on the ebonite lid. The cell is charged by the battery of two

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[1] *Philosophical Transactions*, 1845.

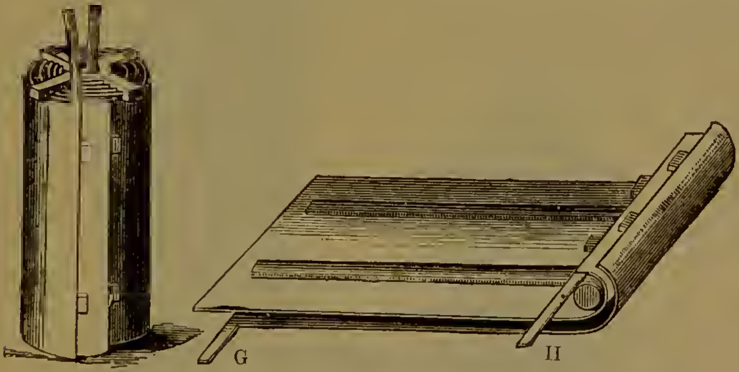

Fig. 24.—The Lead Plates of Planté's Cell.

Bunsen's cells seen at the side, the terminals of this battery being joined to M_1 and M.

When the current from the primary battery is passed through the cell, oxygen is generated at the positive or entering electrode and hydrogen at the negative one. The oxygen acts upon the lead of the positive electrode, and forms a dark chocolate-coloured peroxide of lead on its surface, whilst the hydrogen simply adheres to the negative electrode. The amount of energy stored during this first charge is not very great, though much greater than would have been stored by platinum plates, but Planté showed how the storage capacity may be very largely increased. The process is called *forming* the secondary battery or accumulator, and the object aimed at is to convert one of the lead plates more or less completely into peroxide of

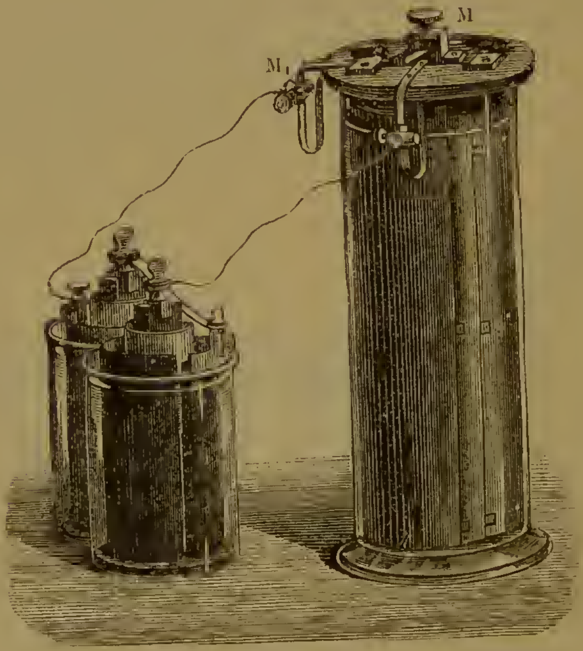

Fig. 25.—Planté Cell with Charging Battery.

lead, and the other into spongy lead. After the first charging current, as already described, has been kept on for fifteen minutes, the cell is discharged, and recharged in the *reverse* direction for a slightly longer period. At this second charging the surface of the plate, which was before peroxidised, is reduced to the condition of spongy lead, and in this condition exposes a much greater surface to the action of the current. The quantity of spongy lead formed depends upon the extent to which the oxygen bit into the lead plate during the first charge. The cell is now again discharged, and then recharged in the same direction as at first for a still longer period. This process of charging alternately in opposite directions with intermediate discharges is continued until the time of charge has reached two hours, the charging current being in all cases kept on until gas bubbles rise freely from the plates. It is then left charged all night, discharged the next day, and again charged, this time without reversal. It may now be left for eight days and the process then repeated, and continued at intervals extending over several months. In this way the storage capacity becomes enormously increased; but unfortunately, when the chemical actions have extended throughout the whole mass of the original lead and the storage capacity has reached its maximum, the plates disintegrate and fall to pieces, as they have during the process of formation lost almost all mechanical cohesion.

The value of Planté's work was early recognised, and various attempts were made to shorten the period of formation and to prevent the ultimate disintegration of the battery. The first of these objects was very successfully attained by Faure, who, in 1881, constructed a cell in which the lead plates, before being rolled up, were coated with a paste of red lead (Pb_3O_4), kept in its position by sheets of parchment and felt. On being placed in the acid the red lead, which is a compound of lead monoxide and lead peroxide, is converted into lead sulphate and lead peroxide. When the charging current is passed through the cell the lead sulphate on the positive plate is converted into lead peroxide, and the sulphate and peroxide on the negative plate are reduced to spongy lead. The cell is thus completely formed in a much shorter time than is necessary for the formation of a Planté cell. Fig. 26 shows a pattern of the Faure cell designed by Reynier.

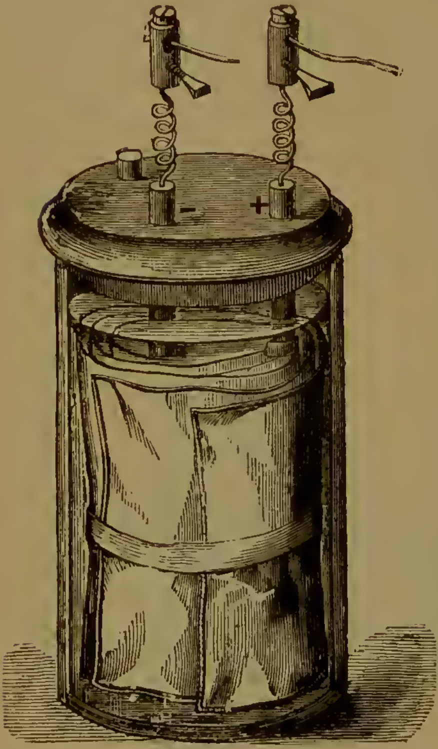

Fig. 26.—The Faure Cell.

The chemistry of the lead secondary battery is not quite so simple as would appear from the foregoing remarks, and to enter into it fully would lead us too far into purely technical details. Lead sulphate undoubtedly plays a very important part in the reactions that take place. Speaking generally, one may say that in the process of charging lead sulphate is decomposed, and that during discharge it is again formed; but simultaneously other reactions are in progress. The formation sometimes of a higher sulphate of lead than the ordinary lead sulphate is particularly troublesome, and is technically known as "sulphating."

It will now, we hope, be clearly understood that the function of the secondary battery or accumulator is to act as a storehouse of energy in a form very convenient for transformation into the energy of an electric current, and it is this function that constitutes its commercial value. The electric energy given out by a battery or a dynamo machine can be stored in the accumulator as energy of chemical separation, and is available, when required, for the reproduction of current energy. In another section of this book we shall have something further to say of the advantages of this system of storage.

Before proceeding to describe some of the more recent forms of accumulators, we must draw attention to a point connected with the nomenclature of the subject which sometimes causes confusion. The plate that is connected to the *positive pole* of the *charging* battery or dynamo is called the *positive plate;* when the accumulator is discharging this plate acts in the same way as the negative plate of a primary battery (*see* page 42). To avoid the confusion that would arise from calling it by different names when charging and when discharging, it is the custom to call this plate *always* the positive plate, and the other the negative. As the positive is the plate on which the peroxide is formed, it has a dark brown or puce colour. The *negative* plate, on the other hand, has a *grey metallic* appearance. The difference between this nomenclature and that of the primary battery should be carefully noted. In the accumulator the positive pole is metallically connected with the so-called positive plate, and the negative pole with the negative plate. Whether the cell be charging or discharging, the positive pole is always at a higher potential than the negative pole.

MODERN SECONDARY BATTERIES.

When the Faure secondary cells began to be used for commercial purposes with large currents of charge and discharge, certain inconveniences in their working manifested themselves to such an extent, that many practical men formed the opinion that they could never be successfully utilised anywhere but in a laboratory.

Prominent amongst these inconveniences was the buckling or bending of the plates, due to unequal expansions of the material on the two sides. Since the plates were placed as close as possible together, this bending frequently resulted in a positive and negative plate coming into contact *inside* the cell, thus closing the circuit internally and heavily discharging the cell. Then, again, in some cells a quantity of white insoluble material, chemically a sulphate of lead, sometimes spread itself all over the plates, and having a high electrical resistance, rapidly stopped the action. The use of felt or parchment to hold the peroxide of lead on the positive plate had very soon to be abandoned, as it quickly rotted and fell to pieces under the continuous action of the acid. These and other difficulties were faced by numerous inventors who, with untiring energy, set themselves the task of overcoming them. The net result is that the storage battery of to-day is a very different thing, mechanically and electrically, though not chemically, from the battery as it left the hands of Planté and Faure.

Mechanically, the cell is more compact, lighter, and the plates are better supported, and kept apart, and less liable to buckle than in the older types. Electrically, the internal resistance has been considerably reduced, and the rate at which current, and therefore energy, can be drawn from a battery of given weight has been largely increased. The arrangements for making electrical connection with the plates, and for insulating the battery, have been made more perfect. It would be wearisome, and lead too much into technical details, to follow each step of the various improvements. We propose instead to describe one or two recent forms, which the reader can compare with the earlier forms already described, and we must refer him to special works on the subject should he desire to pursue it further.

The actual form given to any particular type of cell depends to some extent upon the purpose for which it is designed. Thus it may be employed for house lighting, for central station work, for the traction of tram-cars, for shop lighting, and so forth; each class of work entailing some modification in the construction, and frequently altering the outward appearance of the cells. In all cases, however, the various plates are built up relatively to one another in the manner seen in Fig. 27, which represents a lighting cell of the Electrical Power Storage Company, the owners of the leading patents. This cell is specially designed to give high

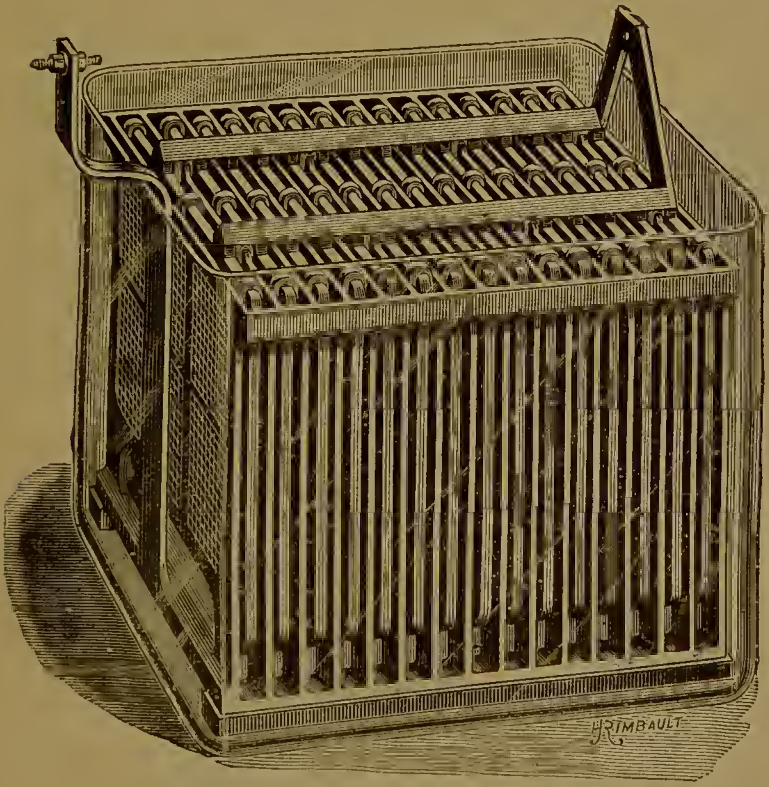

Fig. 27.—E. P. S. Accumulators for Rapid Discharges.

rates of discharge. The first point to notice is that, instead of being formed from sheets of lead made up into a roll, as in the early Planté and Faure cells, the positive and negative plates are perfectly flat, and that the cell is built up of these flat plates arranged alternately in the box and facing one another. The alternate plates are connected together by suitably placed lugs burnt into broad straps of lead, which run the whole length of the cell. In this way all the positives are joined together to form one large positive plate, and all the negatives to form one large negative plate; the two sets of plates having such a large surface, and being so close together, the internal resistance of the cell is extremely small. Experience has shown that it is advisable to have the negative plates one more in number than the positives, as this tends to prevent the disastrous buckling already referred to. Thus the two outside plates are grey negatives, with brown-coloured positives next to them, and afterwards negatives and positives alternately.

All modern secondary batteries for heavy work are made as above described, but they differ amongst themselves in the size, shape, and weight of the plates, in the positions of the connecting lead straps, and especially in the methods adopted for *forming* the plates, and for retaining the active material in close adherence to them. In Fig. 27 there are fifteen positive plates which are thicker than the negative, and have two lugs on each plate projecting upwards from the top, and burnt into the two thick straps of triangular section which will be seen running across the top of the cell. These straps are connected by an inverted V-shaped piece of lead which forms the positive terminal of the cell. As a matter of fact, the positive plates hang from the straps, which are supported on the tops of some of the negative plates with proper insulating material between. The sixteen negative plates are more elaborately connected. Each plate has four lugs—two projecting horizontally at the top corners, and two vertically downwards at the bottom corners. The correspondingly placed lugs are connected by lead straps which stand out quite clear of the positive plates. These straps form a very substantial framework which firmly holds the negatives in their places. At the left-hand side it will be seen that the two bottom straps are joined by a thick cross-piece of lead, to which the negative terminal, consisting of a broad flat piece of lead, is attached. We must not neglect to notice that the bottoms of all the plates are considerably above the bottom of the containing vessel. This is important, as it allows any active material which may become detached from the plates to fall away clear of them; if this loose material remained between the plates, it might bridge the narrow gap and thus short-circuit the cell.

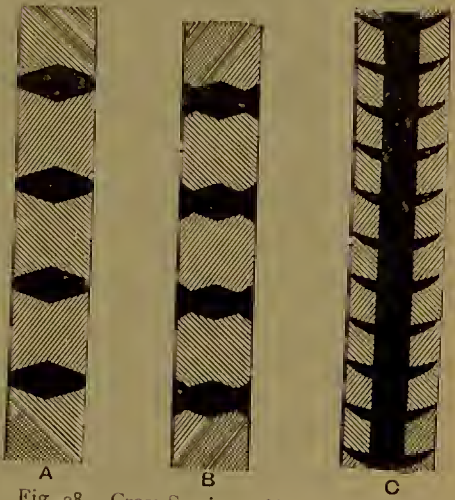

Fig. 28.—Cross Sections of Various Plates.

But it is in the formation of the plates that the greatest differences occur amongst the various batteries that are now in practical use. Each plate, whether positive or negative, consists of a leaden backing or framework of some kind, which is either covered or permeated with the material in which the chemical actions of the cell take place, and which is usually called the active material. In the cell shown in Fig. 27 the negative plates consist of a leaden framework or "grid" with holes about a quarter of an inch square. The ribs between the holes have a peculiar cross section, designed to strengthen the plate and retain the active material in the holes. Three forms of cross section are shown in Fig. 28.

A is a somewhat early form, and B is a more recent form introduced by Messrs. Drake & Gorham. A paste of litharge (an oxide of lead) is filled into the holes of the grid, and is reduced to spongy lead electrolytically by placing the pasted plates in a trough of dilute acid and passing a weak current

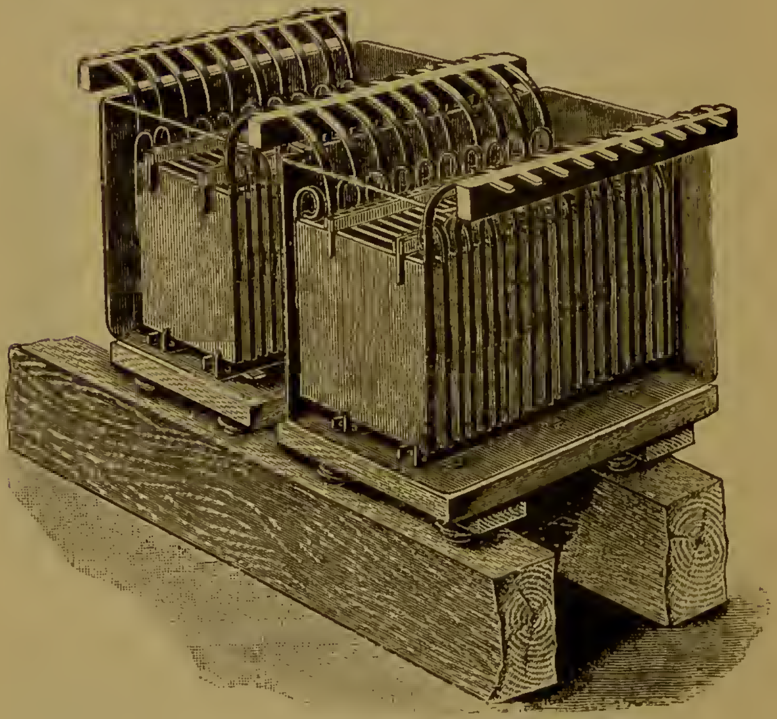

Fig. 29.—Crompton-Howell Accumulators.

through for several days. The plates are connected to the negative pole of the dynamo. The positive plates of the cell shown in Fig. 27 have a lead backing of the cross section represented at C, Fig. 28. A paste of red lead is filled into the grooves, and converted into peroxide by placing the plates in acid and passing a much denser current through them than that used in forming the negative. In this case, the plates are connected to the positive pole of the dynamo.

Quite a different type of cell, also designed to admit of heavy discharges, is the Crompton-Howell cell, Fig. 30. By a well-known metallurgical process blocks of lead are obtained in a highly crystalline and porous condition. These are then sawn into plates of convenient size, some of which are coated with peroxide for positives, and the others with spongy lead for negatives, in both cases modifications of Planté's original process being used. The crystalline nature of the unaltered lead backing presents a large surface in contact with the liquid electrolyte, and mechanically holds the active material in its place. The cells illustrated each

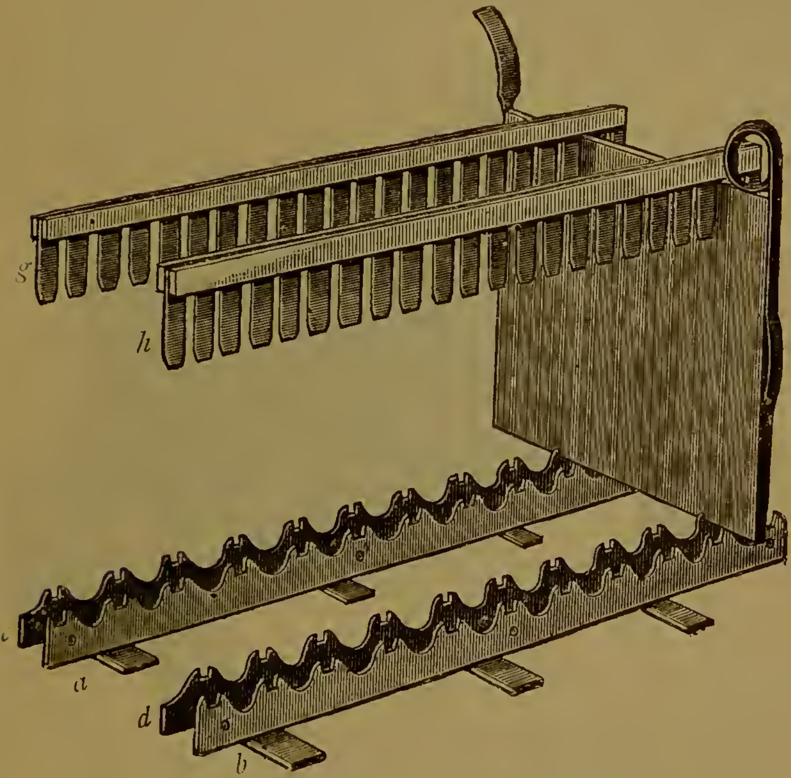

Fig. 30.—Separators in Crompton-Howell Accumulators.

contain ten positive plates and eleven negative ones; the positive plates of the first cell and the negatives of the second are all autonomously soldered to a heavy lead bar, thus eliminating the resistance of clamps. At the bottom the plates rest upon the celluloid separators shown in Fig. 30, the negatives upon *a* and *b*, and the positives on *c* and *d*. At the top they are kept apart by the celluloid combs *g* and *h*. It is claimed for these cells that they have a high efficiency, and are very free from buckling, even when discharged at an excessively high rate.

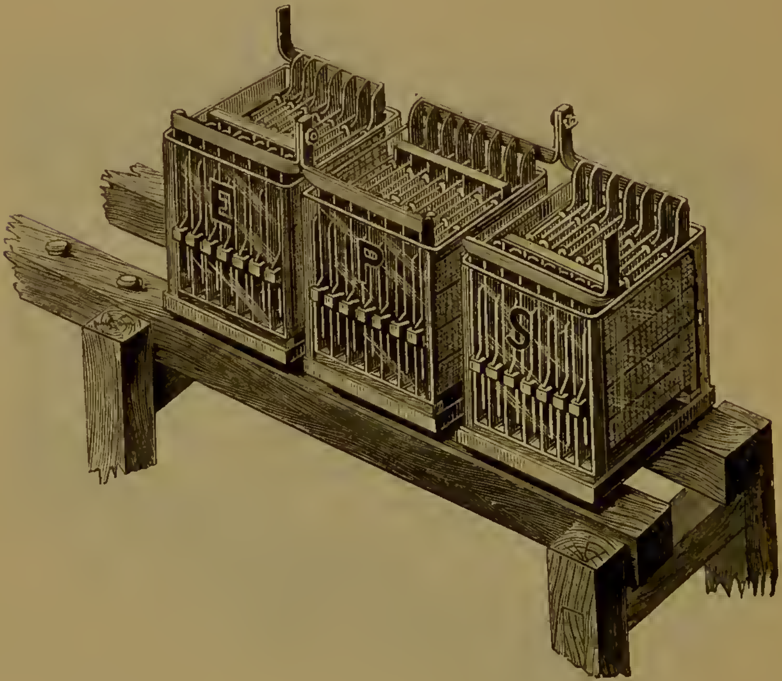

Fig. 31.– Cells for Electric Lighting.

In Fig. 31 there are shown three of the cells of the Electrical Power Storage Company of a type largely used for domestic electric lighting. They are represented supported on trestles, and joined up ready for use, the whole battery probably consisting of fifty-six such cells. Each cell consists of seven positive and eight negative plates, and the positive and negative connecting bands are alternately at the back and the front, the positive band of one cell being tightly clamped to the negative band of the next, so that the whole of the fifty-six cells are eventually joined in "series." The cells do not rest on the wooden trestles directly, but on oil-insulators, which are described later on (Fig. 34). Such

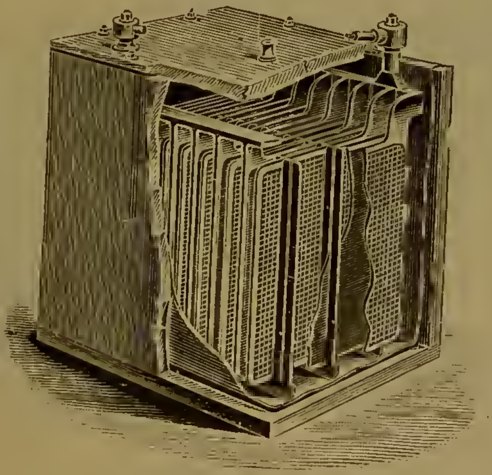

Fig. 32.—Accumulator for Driving Tramcars.

a battery, when fully charged, should light fifty glow-lamps of 16-candle power each for ten hours.

To show how Accumulators are modified in detail for special purposes, we give in Figs. 32 and 33 illustrations of the cells built by the Electrical Power Storage Company for tram-cars and for railway-carriage lighting. In each case the cells are of a shape adapted to be placed underneath the seats of the respective vehicles. The cells, instead of being in glass cases, are in stout teak boxes lined on the inside with lead, and with a lid to prevent the corrosive acid being spilt.

Many other types of accumulators, some of them very successful, have been devised, especially on the Continent. In some of these the plates are laid horizontally, and in others there are special arrangements to allow for the expansion and contraction of the active material during the working of the cell. Solid and semi-fluid, or jelly-like electrolytes, have also been tried. But a full discussion of these various devices is beyond the plan of this book, as it would lead too much into technical details.

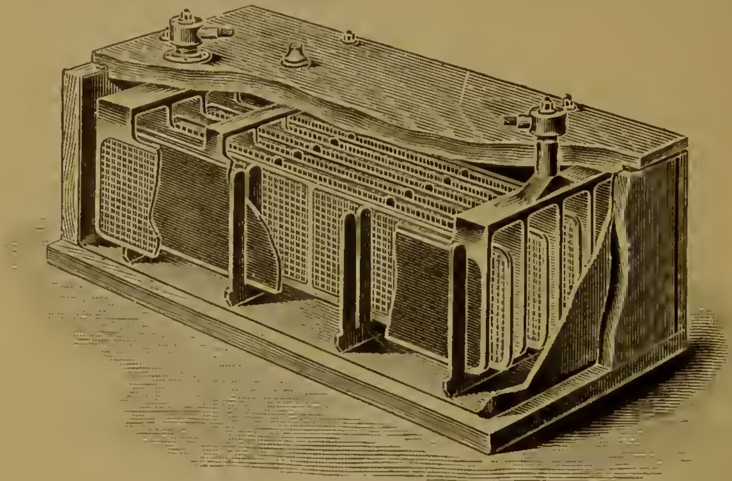

Fig. 33.—Accumulator for Lighting Railway Carriages.

Precautions in Using Accumulators.

As many private houses now have accumulators installed for lighting purposes, it may not be out of place to refer briefly to a few of the simple precautions which should be observed in the treatment of them.

For all accumulators permanently fixed, a dry room should be provided, and suitable trestles erected on which to stand the cells. These trestles should be made of well-seasoned wood, and coated with insulating and acid-proof paint. Each cell should be placed in a shallow wooden tray containing a little loose, dry sawdust, and this tray should be stood upon insulating blocks. A convenient and ingenious form of oil insulator is used by the Electric Construction Corporation, and is shown in Fig. 34. The top part of the figure is a perspective view, and the lower part a section. The insulator consists of two parts, an upper and a lower; the former rests in a ring-shaped hollow in the latter, the hollow being filled with a non-evaporative and insulating oil. Should the outer surface of the insulator get moistened with acid, and therefore become conductive, the current cannot leak away, because it would have to pass over the dry inner surface and through the oil before it could reach the outer surface of the lower part.

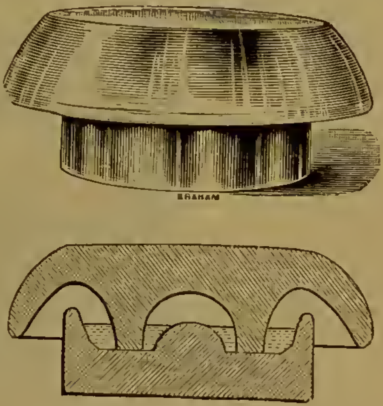
Fig. 34.—Oil Insulator.

The positive terminal of one cell is permanently and firmly joined to the negative terminal of the next throughout the battery, leaving one positive terminal free at one end, and one negative terminal free at the other. The methods of joining up the battery to the working circuits will be described in a subsequent part of the work.

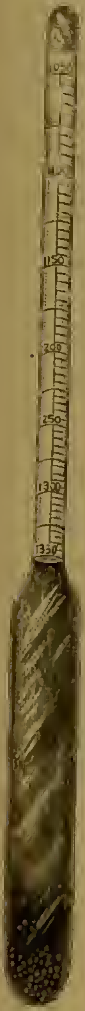
Fig. 35.—Hydrometer for Accumulators.

A few words may be said here about charging and discharging. As a general rule, it may be remarked that it is better to keep the battery overcharged than undercharged. In no case should a discharge be so far continued as to exhaust the battery. There are two ways of ascertaining whether a cell is sufficiently charged or discharged. The simpler one is by means of a hydrometer which measures the density of the acid. We have already remarked that, in charging, sulphuric acid is formed, and in discharging it is absorbed by the plates. Assuming that acid of proper strength has been put into the cells when first they were set up, the density of the acid may be used as a test of the state of charge. For this purpose a special form of hydrometer is used. The lower part (Fig. 35) is flat, and with the stem can float between the closely packed plates. As the cells discharge, the hydrometer sinks further and further into the liquid, and when it registers a density of 1·150, the discharge should be stopped. In charging, the reverse occurs.

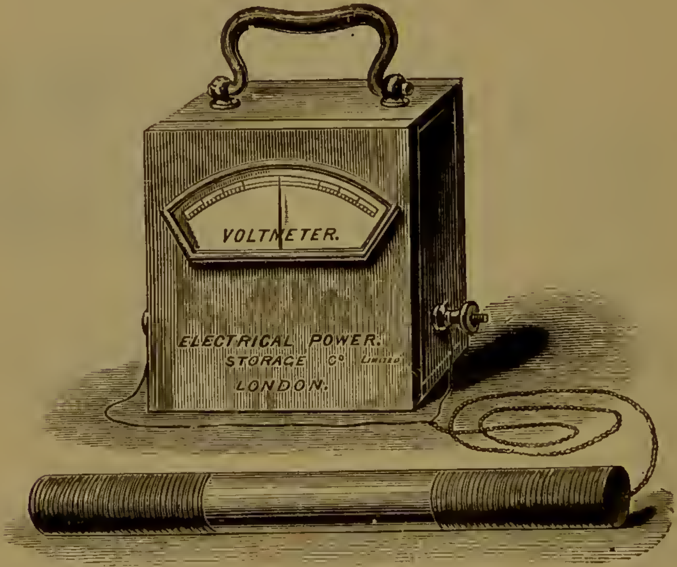

Fig. 36.--Single Cell Voltmeter.

the limit being 1·200, but a good criterion is to continue the charging until gas is given off freely. These figures apply to E.P.S. cells.

The other method of testing the cells is by means of the voltmeter, a special form of galvanometer (*see* p. 387). A convenient modification is shown in Fig. 36. A wooden rod is provided with corrugated brass tubes on its ends, which are respectively connected with the two terminals of the voltmeter. When the ends of the rod are placed on the positive and negative terminals of a cell a current flows through the voltmeter and the pointer indicates the pressure of the cell in volts. This pressure should never be allowed to sink below 1·8 volts, and if any cell differs considerably from the other cells of the battery it should be at once disconnected and carefully examined. The working pressure of a single cell is about 2·0 or 2·1 volts.

When a battery is in regular use, the density of the acid and the pressure of each cell should be taken about once a week and recorded. If the battery is to be left unused for some time, it should be first fully charged and then disconnected from all circuits. Also when a battery has been standing idle for some time, it should be fully recharged before being again used.

CHAPTER IV.

THE MECHANICAL OR MAGNETIC PRODUCTION OF THE CURRENT.

In the preceding pages we have described how the production of continuous currents of electricity was first accomplished by chemical means; and it was by using currents so generated that most of the laws of the electric current were discovered and investigated, and many practical applications were successfully developed. But this method of producing electric currents has now been superseded for all purposes where large currents are required, and for many other purposes as well, by a direct transformation of mechanical into electrical energy which depends upon the magnetic properties of the current. Before, however, we can be in a position to discuss satisfactorily the details and principles underlying this method of producing electric currents, it will be necessary to refer briefly to the facts and principles of the cognate science of magnetism, a science whose connexion with electrical phenomena, though previously suspected, was not definitely and conclusively established until the early part of the present century.

Magnetism.

Historical.—In our introductory remarks (p. 2) we have briefly referred to the knowledge of magnetic phenomena which existed previous to the time of Gilbert. This knowledge may be summed up in a few lines. It was known that the lodestone attracted iron, and could communicate this property to pieces of iron and steel brought under its influence, so that these in their turn were able to attract iron and endow other pieces of iron with the same property. The north and south set of a magnetised steel needle, free to turn in a horizontal plane, was also known and applied in the mariner's compass, by trusting to which Columbus had discovered the New World. This appears to be all that was known up to about the middle of the sixteenth century. But not long before Gilbert's experiments, Hartmann and Norman had independently observed that a steel compass needle so balanced as to be horizontal before magnetisation, was quite out of balance after being magnetised, the end pointing northwards appearing to be the heavier, and "dipping" downwards, so that the needle had to be rebalanced to restore it to its horizontal position. This phenomenon, known as the inclination or "dip" of a magnetised rod, has been developed into a particular form of magnetic needle known as the dipping needle. Also the well-known magnetic law, to which we shall refer in detail presently, concerning the attraction and repulsion of dissimilar and similar poles, appears to have been discovered not many years previous to 1576, but the name of the discoverer is not known.

Besides discovering and accurately measuring the dip, Norman had, by a series of simple experiments, proved that the action on a magnetised needle free to move, to whatever cause it might be due, was simply *directive*, and that there was no resultant force of translation. The cause of this action was a fruitful subject of wild conjecture, some supposing the attracting point to be situated in the heavens, others supposing it to be in the earth, and others again supposing the attraction to be due to huge mountains of lodestone situated near the north pole. So far was this latter theory carried, that it was confidently asserted that ships sailing near these mountains had to be put together with wooden nails instead of iron ones, as the latter would be instantly drawn out by the magnetic attraction, and the ship destroyed.

Gilbert originated the bold and simple theory that all the facts of terrestrial magnetism can be accounted for by the assumption that the earth itself is a huge magnet. This theory he supported by experiments on magnetised spheres, which he called "terrellas," or "earthkins." Fig. 37, copied from Gilbert's book, shows one of these "terrellas," with small magnets placed in various positions round it to demonstrate the similarity between its action and the action of the earth on compass needles, as observed by the various navigators and others who had investigated it in different parts of the earth. The promulgation of this theory was only one of the many contributions of Gilbert to the science of magnetism. Indeed, so thorough was his work, that most

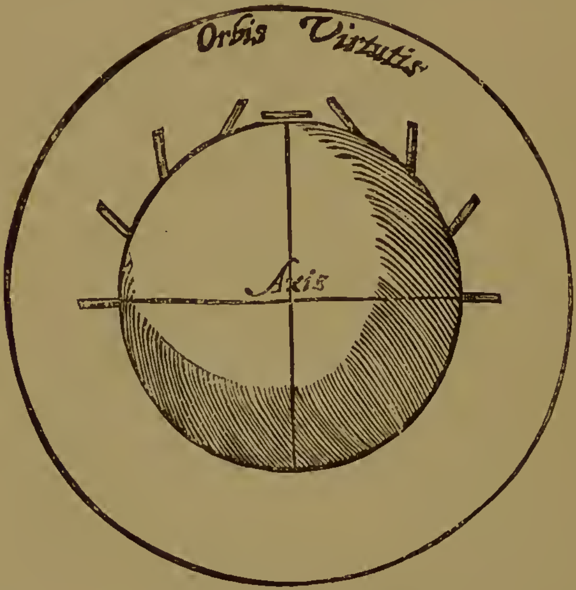

Fig. 37.—Gilbert's Terrella.

of the writers on this branch of physical science for many years after his death did nothing to extend the subject beyond the point at which he left it. Poggendorff has called him the "Galileo of Magnetism," and as many of his observations have not been superseded in the subsequent development of the science, but still form an integral part of it, it will perhaps be more convenient, in order to avoid repetition, to at once lay before the reader the experimental and other data at our command. In doing so, we can most conveniently point out those parts which are due to Gilbert, as well as the extensions made during the last three centuries by those who followed him.

The *lodestone*, the earliest form of magnet, is an ore of iron known to mineralogists as *magnetite*, and having the chemical constitution denoted by the formula Fe_3O_4, that is, its molecule is supposed to consist of three atoms of iron united to four atoms of oxygen: it is thus an oxide of iron. The ore is found widely diffused in different parts of the earth, and sometimes occurs in octahedral crystals; when first obtained from the mine it usually, but not always, exhibits the magnetic properties which first attracted attention to it. These are most easily shown by rolling or dipping the stone in dry iron filings, when it will be found that the filings adhere in tufts to certain parts of it. In a good specimen, two distinct tufts will be formed, but there may be more.

Besides attracting iron, the lodestone can transmit this property to certain other substances. The most convenient method is by rubbing the other body with that part of the lodestone to which the iron filings adhere: these bodies are then found to possess all the properties of the original lodestone, and are said to be *magnetised*. Of all substances, iron, in its various modifications of wrought iron, cast iron, and steel, is capable of assuming this *magnetic* condition in the most marked degree. Next to iron come the metals nickel and cobalt, and a few of the chemical compounds of iron. With a few slight exceptions, no other bodies can be permanently magnetised.

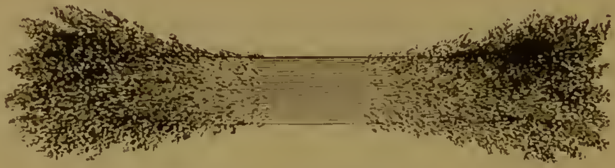

Fig. 38.—Iron Filings adhering to Bar Magnet.

For purposes of experiment, artificial magnets of iron are far more convenient than the lodestone. In one form or another, they are now familiar objects. The ordinary steel-bar magnet, as it appears after being rolled in iron filings, is shown in Fig. 38, the filings adhering to it just as they would to a natural magnet of the same shape. It should be

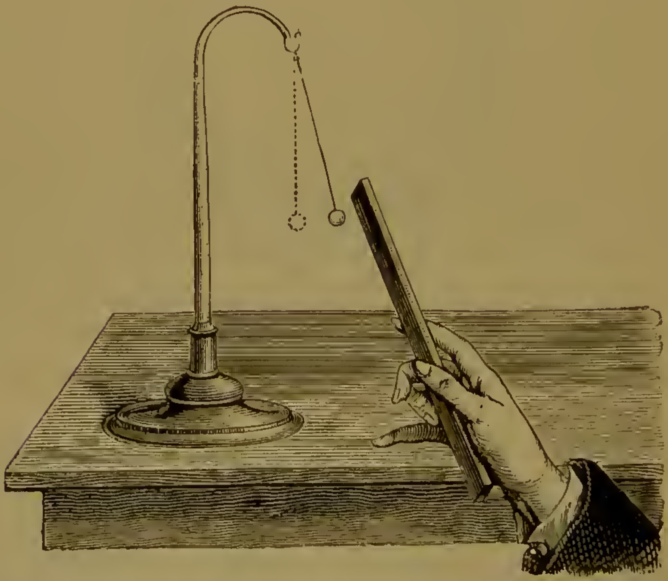

Fig. 39.—Attraction by a Magnet.

observed that the filings cluster together most thickly at the ends of the magnet, and that the central region appears to be unable to attract them. The attraction of the magnet for larger masses of iron can be exhibited by suspending from a suitable stand (Fig. 39) by a long thread a ball of soft iron, and bringing either end of the magnet near it. It will be found that the ball is deflected by the magnet, which is therefore able to overcome more or less the gravitational attraction of the earth. As with the filings, the centre of the magnet will be found powerless to attract the ball. Other bodies may be substituted for the iron ball, and the action of the magnet on them examined.

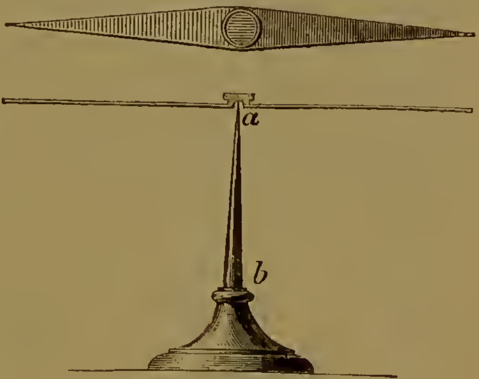

Fig. 40.—Pivotted Magnetic Needle.

The experiment may be instructively varied by mounting the magnet so that it is free to move, and then bringing the bodies under experiment near it. For this purpose, instead of the heavy bar magnet of Fig. 39, a light piece of magnetised steel or *magnetic needle* is usually employed. This may be of the shape shown in Fig. 40, where the double-pointed piece of sheet steel is fitted with a little cap of agate or glass at its centre, by means of which it can be balanced on the fine metal point *a*. Or a convenient length of knitting-needle steel properly magnetised may be hung and

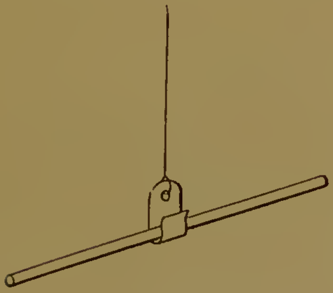

Fig. 41.—Suspended Magnetic Needle.

balanced in a light stirrup (Fig. 41), which is suspended by a long and torsionless silk fibre. Thus, either pivotted or suspended, the magnetic needle is a delicate *magnetoscope* (or magnetism-detector), and it is found to point when at rest in a direction which is approximately north and south. If now the iron ball used in the previous experiment is unmounted and brought near to the needle, it will be found that it attracts *either* end equally well. We may therefore say that the magnet attracts iron, or that iron attracts the magnet. A more accurate experiment was made by Gilbert,

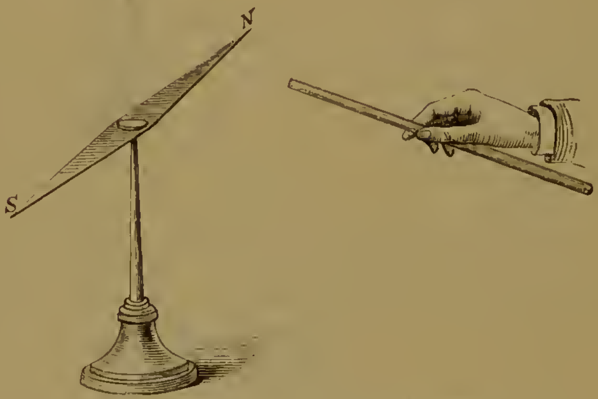

Fig. 42.—Mutual Action of Magnets.

who first hung a piece of iron to the beam of a balance, and, after counterbalancing it with weights, placed a magnet underneath and measured the *attractive* force by adding more weights to the other scale pan. He then attached the magnet to the balance and placed the iron underneath, and found that the attractive force was still the same. The well-known dynamical law of the equality of action and reaction was thus proved for *magnetic forces*.

But the experiment may now be carried further. Let the end of the needle in Fig. 41 which points towards the north (frequently called the north-seeking end) be carefully marked, and lifting the needle from its stirrup, let it be brought near the pivotted needle, as in Fig. 42. If the unmarked end be brought near the north-seeking end (N) of the pivotted needle, it will be found to *attract* it just as the iron ball did, though perhaps more energetically. But if the marked end be presented, it will be found to *repel* the north-seeking end of the movable needle. This is a universal property of ordinary magnets: one part will be found to repel the end (N) of the pivotted needle, and another part to attract it. The parts in which the repelling or attractive force *appears* to reside are called the *poles* of the magnet; and the above experiment shows that the poles which point in the same direction (*e.g.* towards the north) when the magnets are free to move, repel one another, and that those which point in opposite directions attract one another. We are thus led to the well-known law that, *Like magnetic poles repel one another, and unlike magnetic poles attract one another.* As already remarked, this law appears to have become generally known about the last half of the sixteenth century. We shall, in what follows, refer to the part of a simple magnet which *repels* the north end of a freely suspended magnetic needle as the "north pole" of the magnet, and the part which repels the south end of the needle as the "south pole."

Experiments similar to the above led Gilbert to draw a distinction between *magnets* and *magnetic bodies* or substances. The latter attract either end of a freely suspended magnet indiscriminately, and without regard to which part of the body is presented to the magnetic pole. Whereas magnets either attract or repel, but only near their poles, and there is a neutral or equatorial region near which external magnetic force is either absent or very feeble.

Another important observation is that it is impossible to obtain a magnet with only one pole. If we try to separate the two poles by breaking a long magnet at its middle point, near which, as just observed, there is little or no magnetic force, it will be found that each piece is a complete magnet possessing *two* poles. The parts of the metal near the middle of the original bar, which showed no action before, are now strong poles. Again, no method of magnetising can give us a magnet with one pole, though a badly magnetised bar may have more than two polar regions. The effect of dipping such a bar in iron filings is shown in Fig. 43. Besides adhering at the ends, the iron filings also adhere at intermediate places. On testing these places with the magnetoscope already described, they will be found to exhibit alternately north and south polar properties. Thus if the end (N) of the bar be a north pole, as proved by *repelling* the north-seeking end of the pivotted needle, the region A will exhibit south polarity, the region B north polarity, the region C south polarity, and the other end (N^1) will be found to be a north pole. These intermediate regions (A, B, and C) are called *consequent poles*, and can be produced by rubbing the bar in an irregular manner when magnetising it.

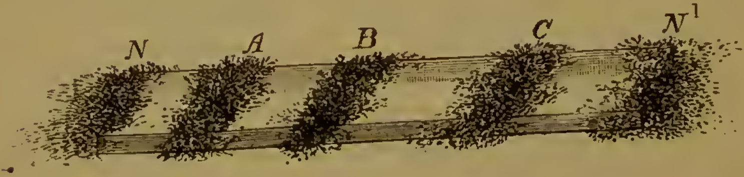

Fig. 43.—Badly Magnetised Bar with Consequent Poles.

It was known in early times that the magnetic attractions were not interfered with by interposing brass and some other substances between the attracting bodies. Gilbert experimented with many substances, amongst others with rings of flame surrounding a magnet, and he found that the magnetic attraction acted across the flame. Experiments show that whatever materials fill the intervening space between the attracting bodies, provided only that there are no *magnetic bodies* (*see* p. 97) there, the magnetic forces still act across the space. The only way in which a magnet, or magnetic body, can be *screened* from being affected by other magnets in its neighbourhood, is by enclosing it in a thick *shell of iron* or other magnetic material. Such a screen is used in Lord Kelvin's marine galvanometer.

The distinction drawn above between magnets and magnetic bodies would seem to point to a difference in the magnetic actions called into play when the two classes of bodies are examined in the manner suggested by bringing them near a freely suspended magnet. In reality, the distinction is more apparent than real, for it is easy to show that the attractions in both cases are attractions between *magnets*, and follow the polar law of attraction already enunciated. What, then, is the difference? It is this. The magnets already possess polar properties before being tested, whereas the magnetic bodies *temporarily* acquire these polar properties by the mere fact of being brought near to, or *into the field* of, the suspended magnet. Moreover, the polarity assumed whilst near the latter is such that an *unlike* pole is turned towards the nearest pole of the magnet in all cases, and therefore we get *attraction* always. On removal the magnetic bodies either lose this acquired polarity completely; or retain such a feeble trace of it that when brought in the same manner near the opposite pole of the suspended magnet, they become polarised in the opposite direction, and attraction again takes place. The magnetic body, when temporarily magnetised as above, is said to be under induction; and the phenomena exhibited are due to a particular class of magnetic actions which form an important branch of the science under the name of *magnetic induction.*

Magnetic Induction.—That a magnetic body placed near a magnet is for the time being polarised, and itself a magnet, can be shown by a number of striking experiments, from which we shall select one or two. One of the simplest is the following, due to Gilbert. A and B, Fig. 44, are two short pieces of soft iron suspended by long threads, as shown; before the magnet pole (N) of a permanent magnet is brought near to them, they hang side by side in the position shown by the dotted lines. But when either pole—for instance, the north-seeking pole (N)—of a powerful permanent magnet is brought underneath and near to them, they assume the position shown by the full lines. Gilbert explains this action by saying that the two ends of the little pieces of iron nearest to N become poles similar to one another, but dissimilar to N, whereas the farther ends become similar poles to N. We have indicated this state of affairs in the figure by the small letters s, n, s', n'. Now, as the magnetic law is that like poles repel, we have s and s' mutually repelling one another, and likewise n and n' repelling one another. Hence the little pieces of iron take up the position figured. That the ends nearest N are of unlike polarity to N is shown by the attraction between them and N.

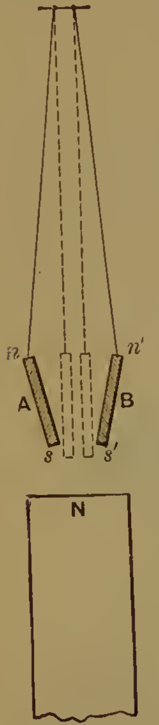

Fig. 44.
Repulsion due to Induction.

Another instructive experiment in magnetic induction is the following:—Let a well-magnetised bar magnet (NS) be clamped in a horizontal position (Fig. 45), and in line with it clamp a rod (A) of well-annealed but unmagnetised wrought iron. A number of iron tacks or nails may now be suspended in a kind of chain from the end (s) of A farthest from NS, and these will be supported, and support one another, by the polar attraction of A, and the mutual attractions of the poles induced in the tacks themselves. But this state of things only lasts as long as NS is kept in position. If NS be removed to a distance, all magnetic action will vanish, and the tacks will drop off from the end of A, which has now ceased to show any magnetic properties.

A great difference is found to exist between different kinds of iron and steel when placed under induction. Broadly speaking, two effects have to be observed. First, the magnetic properties manifested whilst the specimen experimented upon is actually under induction: these properties are due to the so-called *temporary magnetism*. Then there are the properties retained when the inducing cause is withdrawn: these are due to so-called *residual magnetism*. Now, as regards *temporary* magnetism, soft wrought iron carefully annealed is found to give the best results, and as harder and harder specimens are examined, the induced temporary magnetism is found to get less and less until we reach cast iron. Passing then to steel, we find it even worse than cast iron, and the harder the steel, the less temporary magnetism does it show under given conditions of induction. But when we examine the *residual* magnetism, this order of merit is reversed. Steel, which showed such poor results relatively to soft iron when under induction, is found to be able to retain a far larger portion of the properties then exhibited than either cast or wrought iron. In fact, the residual magnetism is not only relatively, but absolutely much greater. It is for this reason that all *permanent* magnets are made of steel. Next to steel comes cast iron,

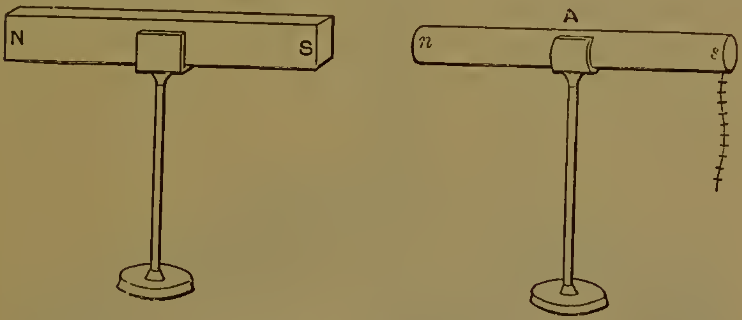

Fig. 45.—Iron Rod under Induction.

and worst of all for retaining magnetism is the wrought iron, which exhibited so much temporary magnetism when under induction. In fact, it may be stated as a general law that those bodies which are most susceptible of temporary magnetisation show least residual magnetisation, and *vice versâ*, or a body easily magnetised also easily loses its magnetism. The most convenient method of investigating the above facts is by means of electric currents, and we therefore reserve details for the present. The property of substances by which they are able to retain a portion of the magnetism imparted to them by induction is known as their *coercive* or *coercitive* force, and Dr. J. Hopkinson has recently shown how a numerical value can be assigned to it (*see* page 156).

Early Magnetic Theories.—So far, we have confined our attention to the most prominent experimental *facts* of magnetic action, but before taking up the consideration of additional recent discoveries, and of more modern ways of regarding those facts, it may be interesting to devote a few lines to considering the explanation which for a long time was regarded as sufficient to account for the phenomena. This explanation came into favour at the time when the glamour of Newton's great generalisation concerning "universal gravitation" largely influenced the direction of the scientific thought of the day. It was therefore natural that men should endeavour to explain any additional cases of attraction that came under their notice in the way pointed out by Newton, namely, by a theory of "action at a distance." It is true that the magnetic case appeared less amenable to this treatment than the gravitation case, since not only attractions, but repulsions had to be accounted for. To meet this difficulty, it was necessary to assume the existence of two kinds of magnetic matter, or magnetism, endowed with opposite properties, such that *magnetism of either kind repels magnetism of the same kind, but attracts magnetism of the opposite kind.* The manner in which the distance apart of the acting magnetisms affected the attractions and repulsions had to be determined, and it is not surprising that the celebrated gravitational "law of inverse squares" should have been regarded as the most likely one.

The matter was apparently settled in 1785 by a series of masterly experiments by Coulomb with the torsion balance of Michell. This instrument, as used by Coulomb, is shown in Fig. 46. An open wooden box, 3 feet square and 18 inches deep, had a graduated circle 34 inches in diameter fixed horizontally 9 inches from the bottom. A vertical tube 30 inches long was fixed over the centre of the box on a

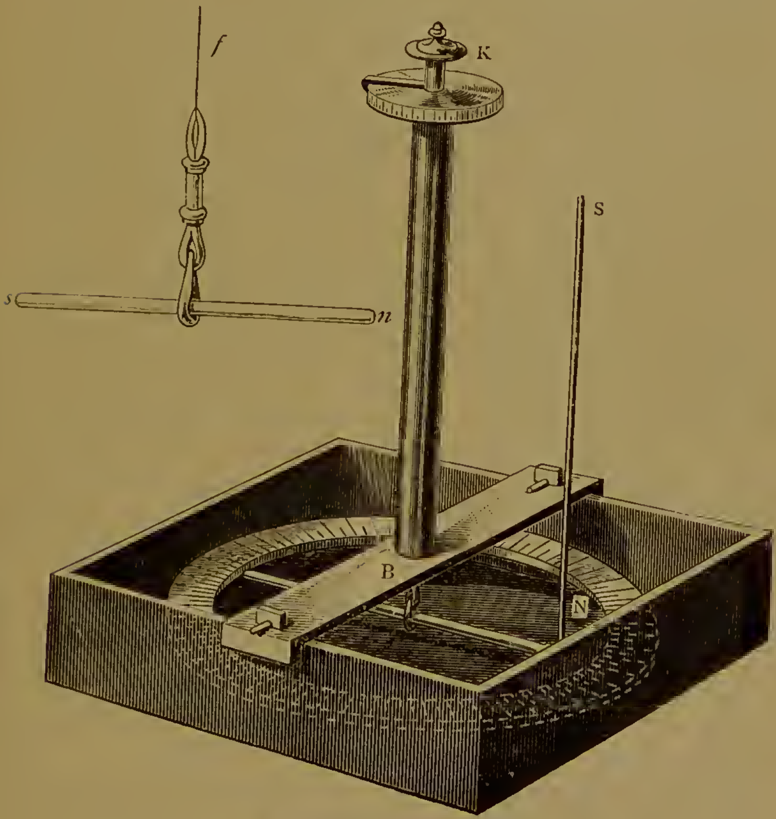

Fig. 46.—Coulomb's Torsion Balance.

cross-bar B and carried at the top a circular plate made fast to a short cylinder, which was fitted so as to turn easily inside the tube. The circular plate was divided into degrees of arc, and from below its centre a fine brass wire was suspended so as to hang freely in the tube. The lower end of the wire was clipped by a stirrup, shown on a larger scale at the side, in which a magnetised steel needle could be balanced horizontally. The needle used by Coulomb was 24 inches long. If now the circular plate at the top be turned, whilst the suspended needle is prevented from turning through an equal angle, a twist or "torsion" will be given to the wire.

In such an instrument, the turning force with which the wire acts upon the suspended magnet in any particular position is strictly proportional to the amount of twist in the wire, or to the angle through which the wire is twisted. This "angle of torsion," as it is called, can easily be ascertained by reading the angular positions of the torsion head and of the suspended magnet on their respective scales. To produce the magnetic action, a second and fixed magnet (NS), the clamps for holding which are not shown, is introduced into the case in a vertical position, with its north pole downwards and near the north pole of the suspended magnet. In Coulomb's experiments, this fixed magnet consisted of a thin steel wire 24 inches long, similar to the suspended needle, and carefully magnetised. When placed in position, the action of such a magnet on the suspended magnet would be almost entirely that due to its N pole. The S pole is almost completely out of action, both because of its greater distance and also because the direction of its action does not correspond with the possible direction of motion of *ns*. In making an experiment, the magnet NS is first removed, and the whole instrument is turned round until the magnet *ns* is brought to rest under the directive action of the earth, with no torsion on the wire *f*. This adjustment is assisted by replacing *ns* by a similar bar of non-magnetic material such as copper. NS is now introduced with its pole N downwards, and consequently the pole *n* of *ns* is repelled, and *ns* takes up a position of equilibrium, but can be brought back to its first position by turning the torsion head (K) in the opposite direction. Suppose in a given case, with N in a certain observed position, that K has to be turned through 300° to bring back *ns* to where it was before NS was introduced. This number (300) then measures the force of repulsion of N on *n*. Now let NS be moved so that its distance from the zero position of *ns* is diminished to one-half of its previous distance, and again bring *ns* back to zero by turning the torsion head. It will now be found that the total amount of turning of the torsion head is three complete revolutions, and about 100° besides. Thus the torsion is $= 3 \times 360 + 100 = 1080 + 100 = 1180$. The force of repulsion has therefore been increased from 300 to 1180, or about four times by halving the distance between the poles. Had the distance been diminished to one-third, the force would have been found to be increased nine times, and so on.

By such experiments, with numerous variations in detail, Coulomb proved for all cases similar to those upon which he experimented the following law of magnetic action :—*The attraction or repulsion between two quantities* (m and m') *of magnetism, supposed concentrated in two points at a distance* (d) *apart, is* $\frac{mm'}{d^2}$, *and is in the line joining the two points.* Or, in other words, the force is directly as the product of the two acting quantities of magnetism, and inversely as the square of the distance between them. The *unit* quantity of magnetism, or *unit magnetic pole*, would therefore be defined as the quantity which would *repel an equal quantity* placed at *unit distance* from it with *unit force.* It is usual to measure the distances in *centimetres*, and the forces in *dynes.* A force of one dyne, though convenient for these measurements, is exceedingly small, as may be inferred from the statement that:—In London the Weight of One Pound =445,050 Dynes.

We have already remarked that the existence of both attractions and repulsions necessitated, for "action-at-a-distance" theories, the assumption of the existence of two kinds of magnetism endowed with opposite properties. In this way arose the celebrated "two-fluid" theory of magnetism, which supposes that all magnetic bodies in the neutral state possess a store in equal quantities of the two magnetic fluids. The process of magnetisation was described as due to the separation of these two fluids, the positive fluid going to the north end of the magnet, and the negative fluid to the south end. These fluids were then supposed to act upon one another according to the law just enunciated. Now, it is undoubtedly true that, with the help of subsidiary hypotheses regarding the distribution of the so-called fluids at the ends of the magnet, this theory was capable of explaining, and mathematically predicting, most of the phenomena known before the discovery of electro-magnetism. Amongst other modifications, it was found that the distance (*d*) referred to above had to be measured, not from the end of the magnet, but from a point within the magnet near its end. Thus, in Coulomb's 24-inch magnets, a point about 1 inch from the end was found to give the best results. This led to the theory that the magnetism was plastered, as it were, over the ends of the magnet like a coat of paint of varying thickness, and that the point referred to, from which distances were to be measured, was the centre of mass of this "surface distribution," as it was called.

The great advantage of this method of regarding the facts was that it was readily adaptable to high mathematical treatment, and gave rise to innumerable problems in advanced mathematics of great elegance and beauty from the mathematician's point of view. It also had a stimulating influence on the development of mathematics, so that for many years after Coulomb's work it was difficult to say whether the science of magnetism was more indebted to mathematics than mathematics was indebted to the science of magnetism. At any rate, a number of important theories in pure mathematics owe their origin to the necessities of this method of analysing magnetic and analogous electrical experiments and problems. Notwithstanding its inability to deal with many modern problems in the science, the method is still retained wherever a taste for mental mathematical gymnastics is cultivated.

The point at which "two-fluid" and all other "action-at-a-distance" theories break down, is in their failure to take account of the internal constitution of the magnet, and of the state and influence of the medium which surrounds it. In consequence of this defect, these theories are quite unsuited to the treatment of the problems which arise when we have to deal with the experimental facts of electro-magnetism and of electro-magnetic induction. Whatever answer may ultimately be given to the question "What is magnetism?" there is no doubt that the phenomenon of magnetisation is a molecular one. We have already (page 97) pointed out that it is impossible to obtain a single north pole by breaking a magnet. This is what happens when the attempt is made. If a large magnet be broken in two, each of the pieces is found to be a complete magnet with two poles. If these pieces be again broken, the resulting bits are still complete magnets; the process of sub-division may be repeated to any extent mechanically possible, and the smallest bit of the original magnet that can be thus obtained is found to be a perfect magnet, possessing both north and south poles. Facts like these, which were amongst the earliest discovered facts of the science, have long since led to the conclusion that the true explanation of the process of magnetising a bar of magnetic material must be sought in the peculiar constitution of its molecules. Thus, a very probable explanation is that the molecules of magnetic bodies are themselves magnets, but that in the unmagnetised body the axes (or lines joining the poles) of these little magnets are turned indifferently in all directions, and that the process of magnetisation consists in these little magnets turning themselves, under external magnetic forces, so as to set their poles pointing more or less perfectly in one direction. This view is supported by the fact that when a rod of iron is subjected to a powerful longitudinal magnetising force it increases in length, and that at the moment the force is turned on, a sharp click is heard, as if the material of the bar were being suddenly strained. The recent researches of Hughes and of Ewing have shown that, in a modified form, this theory is capable of explaining most of the known facts. But before we refer to these researches, we must briefly indicate how the modern method of viewing the phenomena differs from the old "action-at-a-distance" theories.

THE MAGNETIC FIELD.

Let a bar magnet be laid upon a table and covered with a sheet of glass or stiff cardboard, and let a thin layer of fine iron filings be evenly dusted over the top surface of the glass or cardboard. If now the latter be lightly tapped, the iron filings will arrange themselves in definite "magnetic curves," as they are called, such as are depicted in Fig. 47. Each little bit of iron is brought near to or into the *magnetic field* of the large magnet, and when the card is tapped, the jerk allows them to act like a lot of little compass needles, each turning with its longest axis in the direction of the resultant magnetic force at the particular place where it is. Thus the lines of the filings show roughly the direction in which the magnetic forces act in the different parts of the field; or more strictly, they show the direction of the resolved part of the forces in the plane in which they lie, for the actual directions, in some places at least, must be passing obliquely through the glass or card from the bottom to the top side, or *vice versâ:* Because these lines thus indicate the directions of the magnetic forces, they are sometimes called the "lines of magnetic force," or more briefly, the "lines of force." The term should, however, be reserved for lines following the real directions of the forces, and not resolved directions in a particular plane. The term "magnetic curves" is therefore more appropriate for the lines shown by the filings, though if the cardboard be thin, and close down upon the magnet, the distinction is but slight. Then again, the iron filings themselves, as we shall see presently, modify both the direction and value of the magnetic force in their neighbourhood.

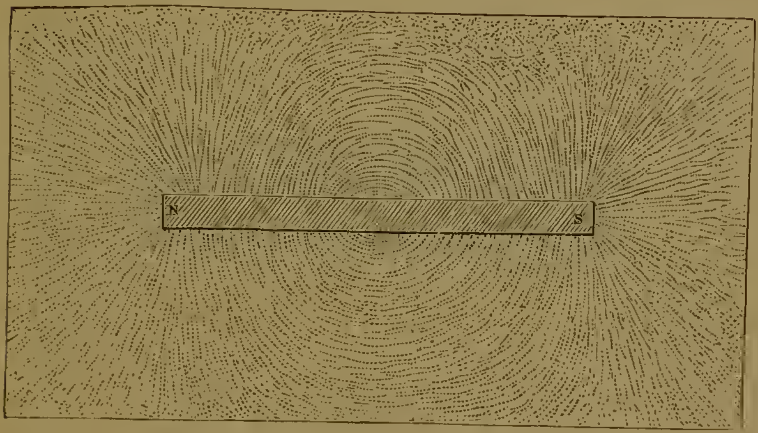

Fig. 47.—Magnetic Curves of a Bar Magnet.

There is another way in which the magnetic curves may be mapped out. Let a very small magnet or compass needle be so suspended as to be free to move in any direction, and let it be brought into the magnetic field, and then moved always in the direction in which either of its poles points. If the course of its movements from different starting-points in a plane passing through the flat magnet be carefully plotted down on paper, we shall get a series of lines such as are shown external to the magnet in Fig. 48. In this case, the lines, except so far as they are disturbed by the presence of the little search magnet, are the actual "lines of force," since the plane chosen is one of the planes in which those lines lie.

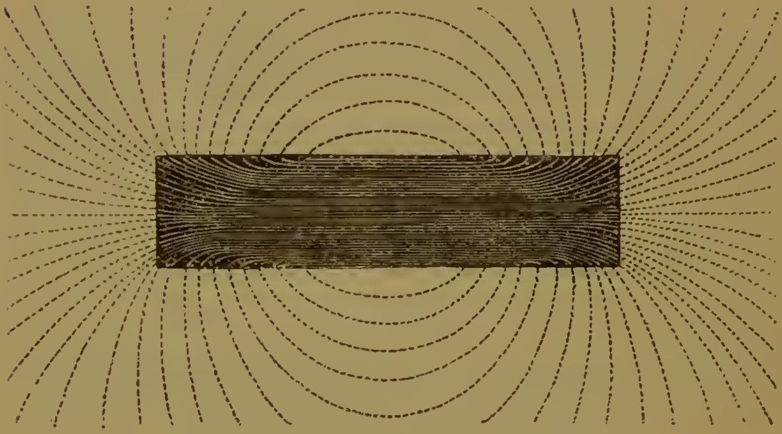

Fig. 48.—Lines of Force of a Bar Magnet.

Faraday, who was the first to point out the importance of these magnetic curves, thus defines them[1]:—"By magnetic curves, I mean the lines of magnetic forces, however modified by the juxtaposition of poles, which would be depicted by iron filings; or those to which a very small magnetic needle would form a tangent."

It should be noticed that, as far as the surrounding air is concerned, these lines all begin and end somewhere on the magnet, and this is a property of all lines of magnetic force

[1] "Experimental Researches," Series I. (1831), par. 114, note.

due to permanent magnets, but not necessarily of such lines otherwise produced. It should also be noticed that they stream out in thick tufts from the ends or poles of the magnet, and are not very numerous near the centre. By drawing them to scale, according to certain rules, we can make them indicate, not only the direction, but also the *magnitude* of the forces at the different parts of the magnetic field; the general result being, that where the lines are close together the force is great, where they are wide apart it is feeble. It is scarcely necessary to point out that iron filings thrown down haphazard cannot give this quantitative delineation of the field, though they may roughly indicate it. Fig. 48, which is drawn to scale, does, however, indicate both the magnitude and the direction of the forces.

Since any line, straight or curved, has two directions at every point of its course, it is necessary to specify the direction which is to be regarded as positive for our lines of force. The convention adopted is that the positive direction shall be that in which a little north-seeking pole, supposed isolated, would tend to move if placed on the line under consideration. Now, we know that one north-seeking pole repels another, and therefore, in our figures, the direction of the lines is that they *start* in the air from the north-seeking poles, and *end* at the south-seeking poles. We might indeed have so defined them, but the more general definition is required when we have no poles in the field.[1]

As a study of these curves is very interesting, we give a few more illustrations of them as mapped out by iron filings, most of the figures being taken from Faraday's "Experimental Researches." In Fig. 49 we have two bar magnets with their lengths in the same straight line, and *unlike* poles nearest to one another. The lines are only shown for the space between and a little way along each magnet. Notice how similar the curves are to those of the single bar magnet in Fig. 47, where the lines were also passing between unlike poles placed very much in the same relative positions; and the curves due to two bar magnets, in line, with *like* poles adjacent, can be inferred from an inspection of the effect of the contiguous poles in Fig. 51.

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[1] It should also be remarked here that the magnitude of the magnetic force itself at any point, is defined as the force which would act upon a *unit quantity* of *north magnetism* (*see* page 105), supposed placed at the point without disturbing the forces of the field.

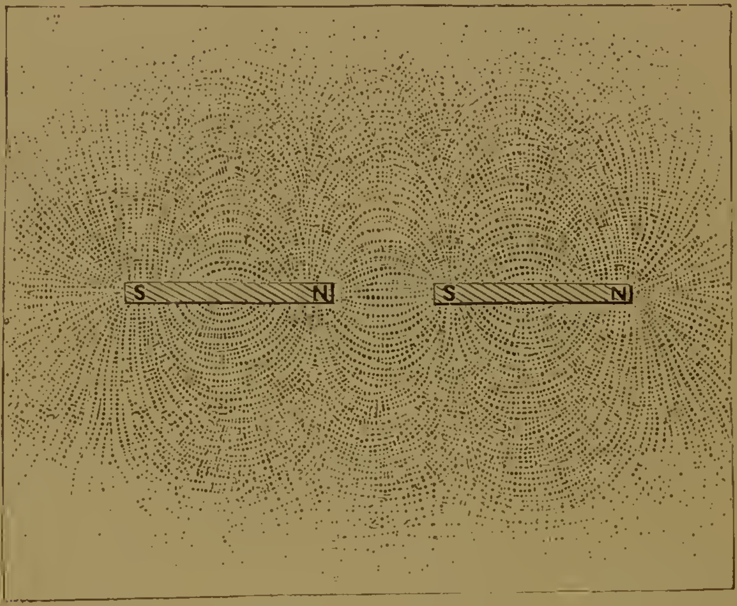

Fig. 49.—Magnetic Curves of Two Bar Magnets in Line.

But the bar magnets, instead of being placed in line, may be placed parallel to one another, either with like poles or with unlike poles close together. The results are shown in Figs. 50 and 51. Notice how the lines issuing from the two similar poles seem to repel and turn aside from one another in a very curious way; one seems almost to get a visible picture of the fact that there must be repulsion between two poles so placed. Also notice in Fig. 50 how the lines issuing from a pole seem to run towards the unlike neighbouring pole, suggesting that there *must* be attraction between these poles.

Let us now consider briefly some of the lessons to be drawn from these curves. The magnetic force (or force on an imaginary north pole of unit strength) at any point in a magnetic field due to permanent magnets can be calculated, for simple cases at least, approximately, by means of the rule given on page 105. This rule regards the action as dependent only on the magnetic strengths of the various so-called poles and their distances apart; we have already pointed out some of its drawbacks. In addition, it ignores altogether the part which the intervening medium may be regarded as playing in the transmission of the action from one pole to another. A little consideration will convince the reader that direct action at a distance, without an intervening channel of communication between the acting bodies, is logically unthinkable. There *must* be a *perfectly*

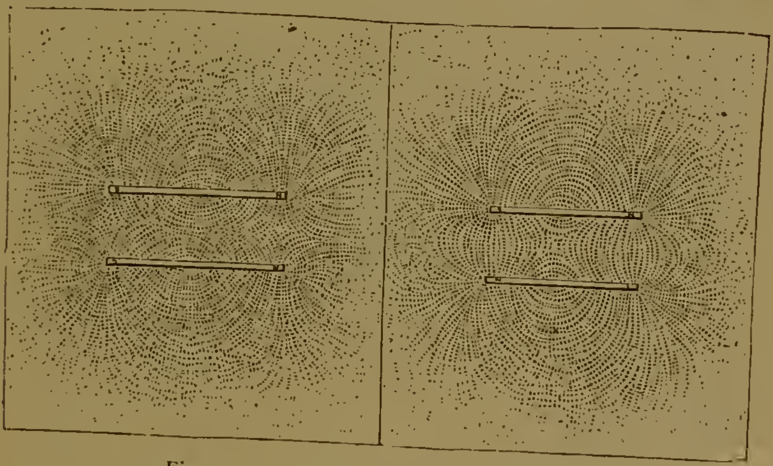

Fig. 50. Fig. 51.

Magnetic Curves of Two Parallel Bar Magnets.

continuous medium interposed, along which the action is transmitted, as a rope or a rod transmits a pull or a thrust from an acting agent to a body acted upon. Or the action may be transmitted by means of waves of various kinds in the interposed medium; the medium is set in motion by receiving energy from the acting body, waves thus started travel through the medium at a definite speed, and part of the energy may produce a particular effect upon a distant body against which the waves strike. The latter method is most appropriate to the transmission of energy by radiations of all kinds, such as those of sound, of light, or of heat, etc., the energy in the intervening space being in the form of a special kind of wave motion. But for all kinds of *steady* actions, where we are concerned primarily with the transmission of force rather than of energy, the action must be chiefly of the kind first specified. Thus in the case of the pull of a magnet on a little iron ball hung over one of its poles by a thread, there must be between the magnet and the ball something of the nature of a rope, along which the pull is transmitted.

We have good reasons for believing that the *something* is the same ether which transmits the sun's light and heat to us through inter-planetary space. But just as the action of the ether in carrying the light and heat waves is modified by the presence of particles of gross matter, so is its action modified in the magnetic case by associating with it the molecules of certain material substances, amongst which iron stands pre-eminent. Thus, in the case cited, we find that the pull of the magnet on the ball is of very different amount if we displace the air that lies between by a lump of soft iron.

Now, if our magnetic pulls and pushes are transmitted from one body to another *through* the medium which surrounds the bodies, that medium must be in a state of strain when transmitting the pulls and pushes. To Faraday belongs the honour of first clearly grasping and utilising this view of magnetic action. By its aid, when he had once obtained the clue, he was led on rapidly to his splendid discoveries in magneto-electricity, and he was also able to give simple explanations of the previous discoveries of Ampère and others. Some of the greatest recent advances in electricity have been due to the application of his method of taking into account the action and modifying influence of the medium. Besides recognising the general character of this influence, he had also a very clear idea of the kind of forces that set up the particular strains which exist in the magnetic field. The impressed forces consist of tensions or pulls along the lines of force, and pressures or pushes at right angles to them. Or if we were to consider the lines of force as having a kind of individual existence, we should regard them as tending to grow shorter in the direction of

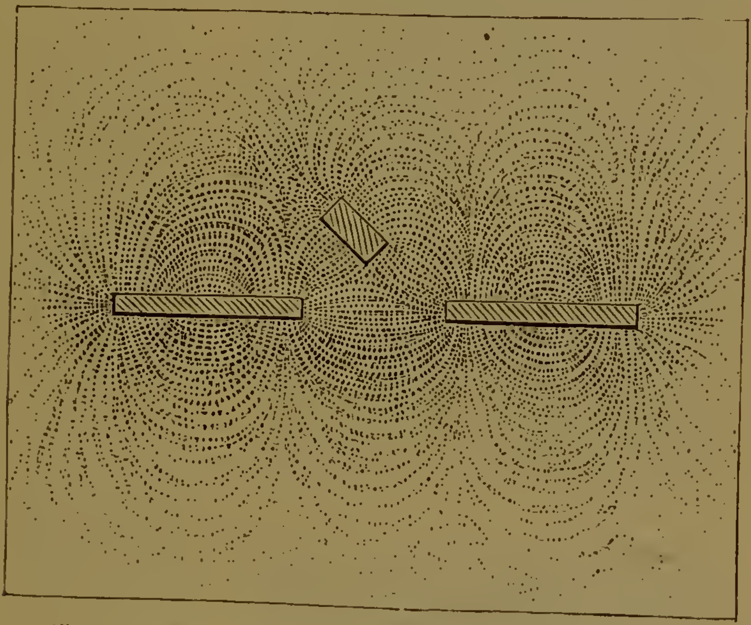

Fig. 52.—Effect of Soft Iron on Field between Two Unlike Poles.

their lengths, but to repel one another sideways. A re-examination of Figs. 47 to 51 will show how this method of regarding the lines would assist one in drawing the various diagrams, and we shall often find it convenient to talk of the lines as if they were real entities.

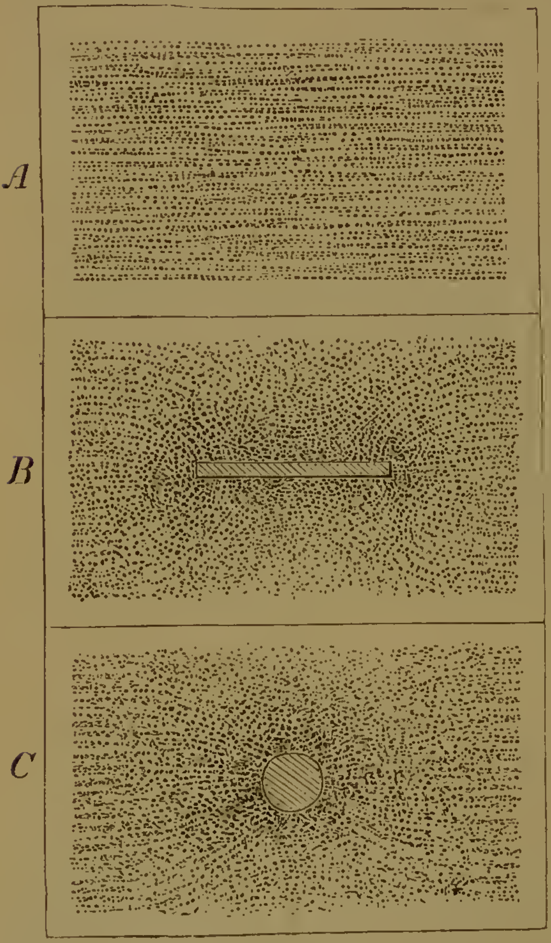

Fig. 53.—Effect of Soft Iron on a Uniform Field.

But to return to the influence of the medium. The iron filings may again be used to indicate the nature of the modifications of the magnetic field due to the introduction of pieces of unmagnetised iron.

If a rectangular block of iron be placed in a skew position between the poles of the magnets in Fig. 49, we get the appearance shown in Fig. 52. Still more striking cases are shown in Fig. 53, which is due to Faraday. Here *A* represents the original state of a magnetic field as mapped out by iron filings; the field is what is called *uniform*, the filings lying evenly in fairly parallel lines. *B* shows the same field when disturbed by the presence of a small rod of soft iron, and *C* represents the effect of introducing a disc of magnetic material into the original field (*A*). Notice in all cases how the lines seem to be attracted as it were by the soft iron, entering in at one part and emerging at another. Or, to put it in another way, it seems as if the lines found it easier to get through the iron than through the air, and as though they tried to get from pole to pole by the easiest path. This latter is perhaps the better way of looking at the facts, and we express it by saying that the *permeability* of the iron is greater than that of the air. This term permeability was long ago used in this connection by Sir William Thomson; a still more modern way of referring to the phenomenon is to say that the magnetic *reluctance* of the iron is less than the magnetic reluctance of the air.

We have just spoken of the lines of force as running through the iron, and in Fig. 48 we have shown the lines as running right through the material of the magnet, each line forming *a closed curve which does not cross any other line.* Are we justified in doing this, or do the lines simply start from and end on the iron and the magnets? We cannot, of course, follow the lines with our iron filings, or our search magnet into the interior of the iron, but two experiments may be cited here as supporting the former view. First, if we cut either the soft iron or the magnet across the assumed direction of the lines, and draw the pieces a little bit apart, we find lines in the gap. This is not conclusive, as their presence there might be otherwise explained. But if the lines run through the iron, the material of the iron should be in a state of strain, or more strictly, the ether within it should be strained, and with it the material which modifies its action. Now, we have already pointed out that when a rod of iron is suddenly magnetised in the direction of its length, it becomes slightly longer, and at the moment of magnetisation a sharp click is heard, as if the material were being strained. The best evidence, however, that the lines really run through the iron is based upon magneto-electric experiments, to which we shall refer later on.

In this way of looking at the facts, a piece of magnetic material is magnetised whenever magnetic lines run through it, and it is permanently magnetised if these lines accompany it when it is moved about.

The "two-fluid" method of regarding the phenomena tends to the same result as the "lines of force" method, if we suppose definite quantities of the north-seeking fluid spread over the parts of the iron where the magnetic lines run out into the air, and similar quantities of south-seeking fluid spread over those parts where the lines run in from the air. But we can have iron very highly magnetised without the lines going out into the air at all, or only passing through the air across narrow gaps. It is useless to attempt to deal with these cases by the two-fluid theory.

The phenomena of induction are therefore to be regarded in this way. Whenever a piece of iron or steel is placed in a magnetic field, however produced, it gathers up into itself, as it were, a much larger number of the magnetic lines than passed through the air which it displaces. It thus becomes magnetised, and has the so-called polar regions on its surface where the lines run in and out. It is found also that if, while it is in the field, it is subjected to vibration or shock of any kind, such as the blow of a mallet, it becomes more highly magnetised, and more magnetic lines run through it. Indeed, the total number of lines in the field may in this way be considerably increased. Considerations such as these have led to the most recent theories of magnetisation investigated by Professor Hughes, Professor Ewing, and others.

According to Professor Hughes, a piece of unmagnetised iron is to be regarded as made up of an infinite number of magnetised particles, each carrying a number of lines of force. But the whole mass appears to be unmagnetised, because these magnetised particles and their lines form closed magnetic chains *inside* the iron, and none of the lines leak out into the air at all. There can thus be no evidence of magnetic polarity. If this piece of iron be now placed in a magnetic field, the magnetic forces of the field tend to turn the magnetic molecules with their axes in the direction of the lines of the external field, and if the molecules are not too rigidly held, they rotate, and the closed magnetic chains inside the iron are opened out. This process is assisted by disturbing and, as it were, freeing the molecules with mechanical or physical vibrations or shocks of any kind. The magnetic lines of the molecules now run out of the iron and complete their circuit through the air or surrounding medium. If, when the iron is removed from the magnetic field, the molecules can rotate with comparative freedom, and again close up their magnetic chains inside the iron, the magnetisation is only *temporary*. This is the case with soft wrought iron. It is *permanent* if the molecular rigidity is capable of retaining the molecules in the directions in which they have been set whilst in the magnetising field. Steel has the necessary molecular rigidity, and hence can be permanently magnetised.

More recently,[1] Professor Ewing has shown that most, if not all, of the phenomena of magnetisation and magnetic induction are imitated by groups of small magnets placed in a magnetic field, whose strength is gradually increased. The little magnets are pivotted on their centres, and placed quite close together, so that they mutually influence one another by the ordinary magnetic attractions and repulsions. As the strength of the influencing field is gradually increased, the external magnetic effect of this group of little magnets passes through very much the same variations as does the external magnetic effect of a bar of soft iron similarly placed in a field of magnetic force whose strength is gradually increased. What these changes are we shall describe fully later on (page 155), but we would here point out that Hughes and Ewing, as well as many other philosophers, begin by assuming that the molecules of the iron are already magnets, and explain the various effects as the consequences of certain movements of the molecules. Some scientists, notably Ampère and Lord Kelvin, have gone a step further back, and have promulgated theories which attempt to explain how it is that the molecules are already magnets. Their explanations present difficulties which experiments have not yet removed, and which lie somewhat beyond the scope of this work.

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[1] *Proceedings of the Royal Society*, Vol. 48 (1890), page 342.

Leaving theories on one side for a time, we propose now to devote a few pages to the remarkable phenomena which are usually classed together under the title of terrestrial magnetism.

Terrestrial Magnetism.

One of the most interesting and important of the magnetic fields that we can possibly investigate is that found to exist at all parts of the surface of the earth on which we dwell. It is interesting because it is always present with us, ready to indicate its existence at all times when sought for by proper methods, and also because, although some of its effects have been known now for hundreds of years, it still presents unsolved problems to the scientist. And it is important because, by its aid, the mariner has been rendered to a great extent independent of the fitful and not always obtainable assistance of the heavenly bodies in guiding his course across the trackless oceans.

We have already referred to the longest and best known of the effects of this ever-present magnetic field. If a magnetised steel needle be mounted (as shown in Figs. 40 or 41) so as to be free to rotate in a horizontal plane, one end of it always points in a northerly direction, and is usually called the north-seeking, or more shortly, the north pole of the magnet. But this is not the only effect, for if a long piece of steel be mounted so as to be free to turn about a vertical axis (as in Fig. 54), and be mechanically balanced before magnetisation, then after it is magnetised, its north pole *dips* downwards in the northern hemisphere, and in some planes the needle will stand vertically. Since a magnetised rod or needle free to rotate on its centre always sets in the direction of the lines of force of the magnetic field in which it is placed, the above facts show that a terrestrial magnetic field does exist, and that the lines of the earth's field are not level, but are more or less inclined to the horizon. The field, however, is too weak to be made manifest by means of iron filings in the usual way. But its general direction in these islands would be represented by a series of equidistant parallel lines drawn parallel to the direction in which the dipping needle sets when turned so as to be free to move in a plane parallel to the horizontal needle or compass. These lines would therefore trend northwards; they would be inclined to the horizontal plane at an angle of about 67°.

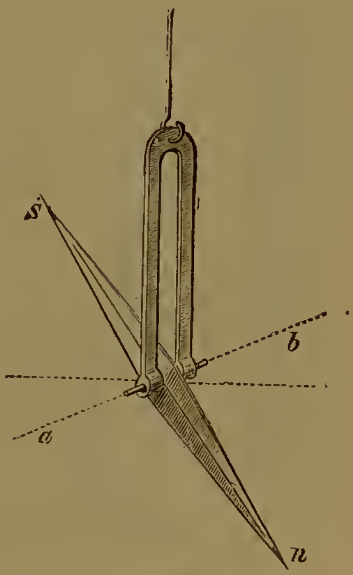

Fig. 54.—Dipping Needle.

The existence of the field can also be discovered by its inductive action on soft iron. Thus if a bar of wrought iron be held parallel to the dipping needle when set as just described, it will be found that the lower end of the bar is a feeble north pole. If, however, the bar, whilst in this position, be struck with a mallet, or subjected to some kind of mechanical shock, it becomes much more strongly magnetised. This is exactly what would have happened if the bar had been put into a magnetic field due to permanent magnets and similarly treated. In this respect, therefore, the earth's field is exactly analogous to the field due to permanent magnets; any difference can be in degree only, and not in kind. Gilbert discovered that iron could be magnetised in this way by the action of the earth alone, and Fig. 55 is taken from his book "De Magnete." It represents a blacksmith hammering a rod of hot iron just taken from the fire; the rod is being held in a north and south direction, as is shown by the words "auster" (south) at the door, and "septentrio" (north) on the adjacent post. When the bar is cooled, and the hammering finished, it is found to be

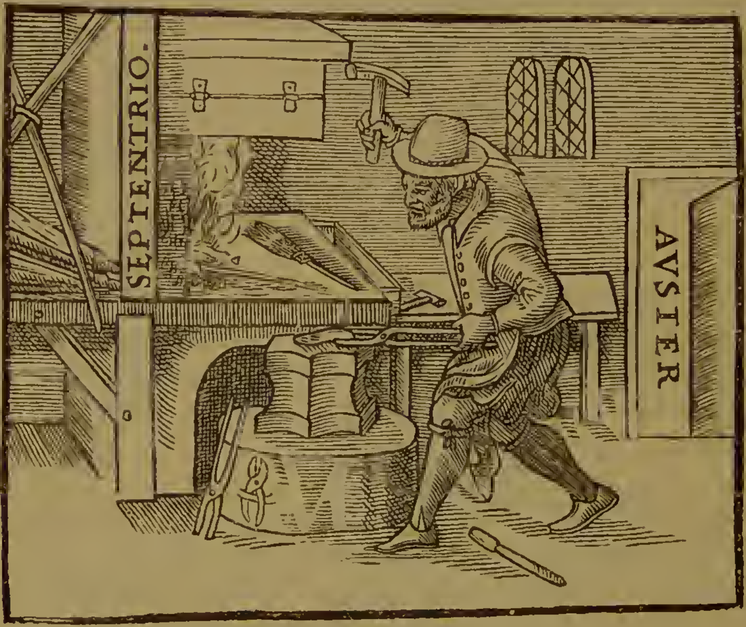

Fig. 55.—Magnetisation of the Earth.

magnetised, with a north pole at the end that was directed towards the north.

Facts such as these led Gilbert to propound the theory to which we have already alluded, that the *earth is a great magnet*, and by aid of this theory he was able to explain all the facts of terrestrial magnetism known at his time. But the positions of the earth's magnetic poles do not correspond with those of the poles of the axis of rotation, or the geographical poles, and it was not until 1831 that the position of the magnetic pole of the northern hemisphere was found by Sir J. C. Ross. It was then situated in Boothia Felix, to the north of North America, in latitude 70° 5′ N., and longitude 96° 46′ W., and was more than 1,000 miles from the geographical pole. The magnetic pole of the southern hemisphere has never been reached, but observations show that it must be situated somewhere on the great ice cap which surrounds the geographical south pole. Certain irregularities in the distribution of the magnetic lines in the southern hemisphere were once supposed to indicate that there are two like poles situated within this region, but it is quite possible that the irregularities are due to local disturbances, and that there is only one true pole.

The Mariner's Compass.—For the purpose of finding the direction of the cardinal points at sea when the sun or the stars are hidden by clouds, a particular arrangement of the horizontally balanced magnetic needle is employed. Such a needle always, when at rest, sets in the direction of the horizontal component of the earth's magnetic force, or approximately north and south. The line along which it points is called the "magnetic meridian," since it indicates the direction of magnetic north just as the geographical meridian indicates the direction of the geographical or true north. But needles supported as in Figs. 40 or 41 would be useless at sea, since the ship on which they are placed is liable to pitch and roll in every imaginable direction. A special kind of mounting is therefore required, and some practical details are added for the purpose of facilitating the reading of the instrument.

Fig. 56 represents the mounting of an ordinary "ship's compass." The needle is pivotted, by means of the cap (C) attached to it, near the mouth of a hemispherically shaped bowl (B); the pivot upon which C rests rises from the bottom of the bowl, which is heavily weighted with lead, so as to lower the centre of gravity below the line on which the bowl is swung. The bowl is suspended in "gimbals," which consist of two short axles (XX), on the same diameter, swinging freely in two holes or bearings in the flat metal ring (RR); this ring in its turn is supported by two other short axles (YY) placed at the ends of a diameter at right angles to XX, and working in two bearings in the outer case. The effect of this system of mounting is that, however the outer case is tilted, the mouth of the bowl remains horizontal, and the pivot vertical, thus counteracting the effect of the rolling and pitching of the ship on which the compass is used. The needle itself is usually concealed by a circular card placed over and attached to it, the position of the north-seeking pole of the needle underneath the card being indicated by some fanciful device such as is seen in the figure. The rim of the card is, as a rule, divided into degrees, and also has marked on it the thirty-two points by which the

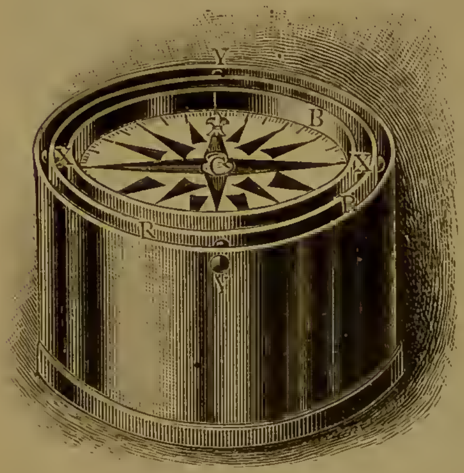

Fig. 56.—Mariner's Compass.

mariner is accustomed to designate the various horizontal directions. The line shown on the inside of the bowl denotes the direction of the ship's "head" as seen from the pivot of the compass; consequently, the direction (magnetic) in which the ship is sailing is denoted by whatever mark on the card is brought by the movement of the compass opposite this line.

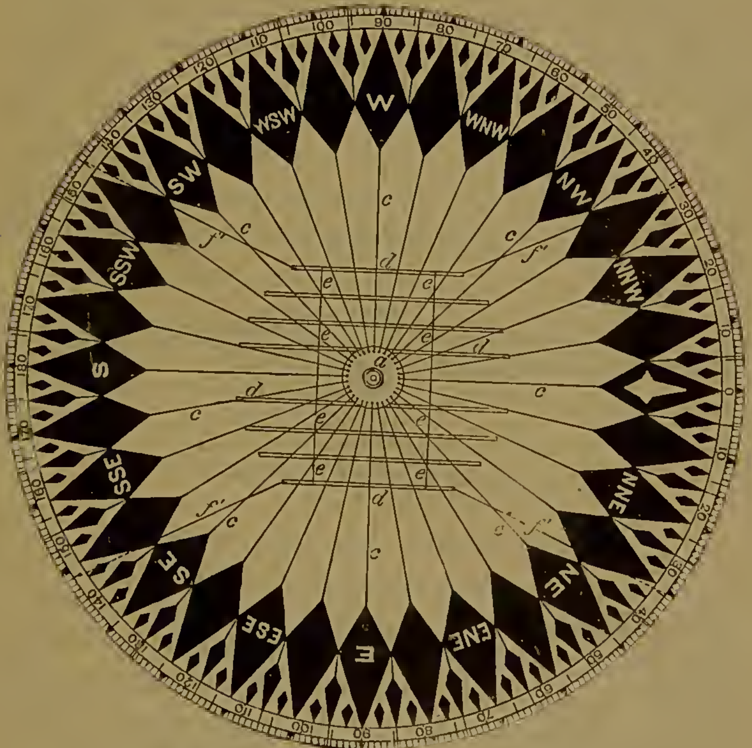

Fig. 57.—Thomson's (Lord Kelvin's) Compass.

But the compass just described is far from being perfect: amongst other disadvantages, the movable part (the card and needle) is so heavy that a fairly large frictional error is possible, and the friction at the gimbals is also too great to keep the compass-box sufficiently level. To remedy these and other defects, Sir William Thomson has invented a much more elaborate compass, which is now widely used. The essential parts of the mounting of the card are shown in Figs. 57 and 58, the latter figure being a section through the supporting pivot. There is a central boss (*a*) with a sapphire or ruby cap (*b*) resting on the pivot; to this boss a light aluminium rim (*f*) is attached by thirty-two fine platinum wires or spokes (*cc*), each one of which passes from a hole in the boss to a corresponding hole in the rim. The compass card, which consists of the circumferential portion only of an ordinary compass card (*i.e.*, the portion containing the marks), is supported partly by the rim and partly by the spokes. The needles are eight in number, placed parallel to one another, and bound together by the fine platinum wires (*ee*); they are then suspended from the rim below the level of the boss by means of the four fine wires attached to holes in the ends of the two extreme magnets of the set. These wires are, of course, attached to such points of the rim as to cause the magnets to hang parallel to the north and south line of the card. In this way a very light movable card and magnetic system is obtained. For instance, a compass 10 inches in diameter, with 8 needles from $1\frac{3}{4}$ to 3 inches long, only weighed 178 grains, and at Glasgow took 38 seconds to make one oscillation when disturbed from its position of rest. To diminish the friction at the gimbals they are swung on knife-edges instead of on ordinary axles and bearings, and to still further steady the case containing the compass, a large bowl of a viscous

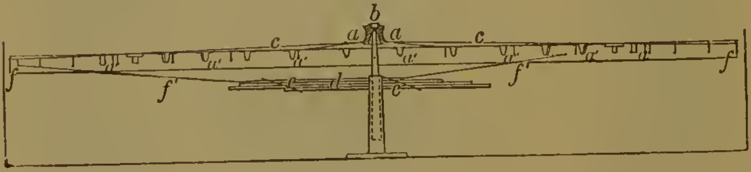

Fig. 58.—Vertical Section of Thomson's Compass.

liquid is attached immediately below the support of the pivot.

We must not leave this part of the subject without referring to a difficulty which at one time threatened to very seriously impair the usefulness of a compass when carried on an iron ship. From what we have already said (page 116) it will be easily understood that the mere presence of the iron of the ship must affect the magnetic field of the earth, to the directive action of which the compass owes its value. But in addition to this it must be remembered, that whilst being built the ship was placed with its head pointing in a definite geographical direction, and was subjected to all kinds of mechanical shocks similar to those to which Gilbert's blacksmith (page 122) treated his iron on the anvil. The result is the same in the two cases, namely that the mass of iron, whether ship or horseshoe, becomes magnetised, and in the case of the ship this magnetism, unless counteracted in some way, must seriously affect the compass. We thus see that when the ship is sailing upon any particular course it is a somewhat complex magnet. There is, first, the permanent magnetism of the ship, given to it whilst on the stocks; and, secondly, the temporary magnetism induced by the earth's field, the magnitude and direction of which relatively to the compass-box will depend upon the direction in which the ship is sailing. The problem of the effect of the various magnetisations on the compass is a complicated mathematical one; it was solved by the late Astronomer-Royal, Sir George Airy, who indicated how compensating magnets might be placed in the neighbourhood of the compass-box. Lord Kelvin has invented methods for placing and adjusting these magnets, and determining any outstanding errors, but these methods are too elaborate to describe here. As an additional precaution for determining the errors of the steering-compass, it is customary to have a special compass mounted at the top of a short wooden mast, so as to be as far away as possible from the iron of the ship.

Declination.—We have seen that the magnetic poles do not coincide with the geographical poles, and as the compass needle always points towards the former, it is evident that only over a limited area of the earth's surface will the needle point to the true north. These places will manifestly be situated where the true and the magnetic poles in the same hemisphere appear approximately in line with one another. At all other places the magnetic meridian will make an angle with the geographical meridian, and the magnitude of the angle will depend upon the relative positions of the place and the true and magnetic poles. This angle is call the *declination*, or sometimes the *variation* of the needle, and is, briefly, the angular error by which the north indicated by the compass-needle is distant from the true north. The fact of the declination was known from very early times, but the discovery that it was different at different parts of the earth's surface was made by Columbus.

As the declination varies from place to place, and at some parts of the earth is a considerable angle, it is very essential that the navigator should know its value for the particular place at which he is. Magnetic surveys have therefore been carefully made all over the navigable oceans, and the declination determined at a sufficient number of points, to allow the results to be embodied on the charts in addition to the other information contained thereon. To determine the declination, it is necessary to find the true north by astronomical observations, and compare its position with the magnetic north as indicated by the compass. The way in which the results are recorded for reference is as follows: A number of points at which the declinations are all of the same value are found, and these points are joined by a line on the chart, the value of the particular declination being marked on the line. Then another series of points is found, all having the same declination, but of a different value from that first obtained. These are plotted down and joined, and then other lines are similarly drawn. In this way the chart finally contains a number of lines along each of which the declination has a definite value, which is recorded on it. Such lines are known as **isogonic** lines, or **isogonals**, or *lines of equal declination*.

On the following page we give a chart on Mercator's projection, showing these isogonals for all parts of the habitable earth and navigable oceans. The lines indicating easterly declination are dotted, and those specifying westerly declination are drawn full. It will be noticed that the line of 20° West declination crosses England from Bristol to the mouth of the Wear, whilst the line of 25° West declination passes through the west of Connaught and through the Hebrides. Between these two lines the declination has values lying between 20° W. and 25° W. There are two main lines of no variation, that is, lines along which the compass points to the true geographical north. One of these passes down through Canada and the lake district of North America, through the United States, the West Indian Islands and Brazil into the Southern Ocean. The other passes down through European Russia, a little to the east of St. Petersburg, through Persia, across the Indian Ocean, and the western corner of Australia. There is also a curious loop of no variation, embracing Eastern Siberia, Japan, and a large portion of China. Wherever a line of no variation is crossed, the variation changes from easterly to westerly, or *vice versâ*.

The lines on the chart, however, only show the general trend of the "isogonals." But even there it will be seen that the regular flow of the lines from one magnetic pole to the other is seriously disturbed over large sections of the

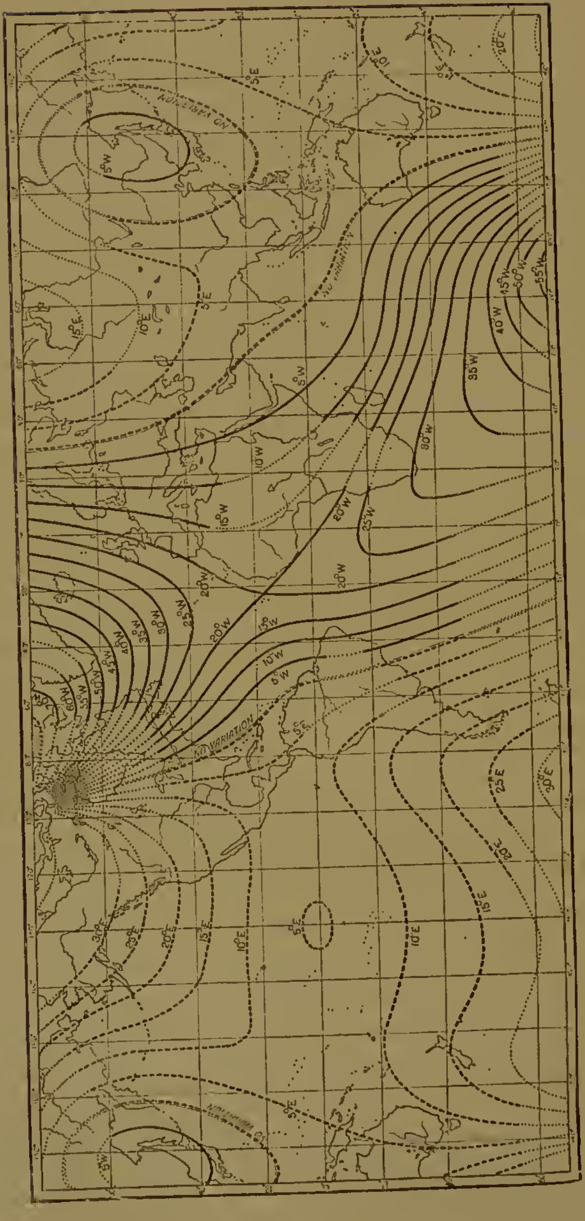

Fig. 59.—Isogonals for the Year 1891.

earth's surface. In addition the lines are affected by smaller "regional" disturbances and still smaller "local" dis-

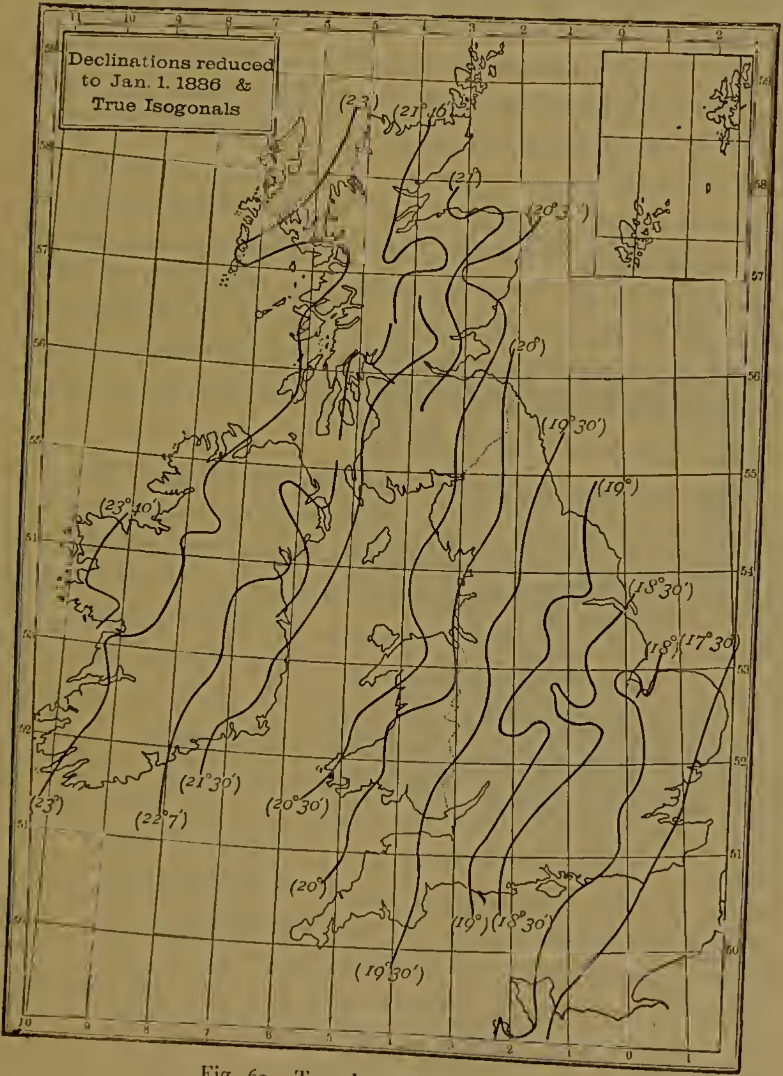

Fig. 60.—True Isogonals for 1886.

turbances. These minor disturbances have been very laboriously investigated by Professors Rücker and Thorpe in a recent research,[1] in which they made a minute magnetic survey of the British Isles. The true isogonals for the year 1886 are shown in Fig. 60, which is reproduced from one of their maps. The lines do not go straight across the country, as might be inferred from the foregoing chart, but are irregular in shape, merely following the general direction of the lines on the chart. From a study of the geology of the districts where disturbances occur, Professors Rücker and Thorpe make the important deduction that these disturbances are due to "the presence of crystalline rocks, and especially of basalt, either visible on the surface, or concealed by superimposed masses of sedimentary strata." It is thus rendered probable that the larger disturbances depicted in Fig. 59 are due to similar causes on a vaster scale.

Dip or Inclination.—The dipping needle, when free to move in a vertical plane containing the magnetic meridian, makes a definite angle with the horizontal plane; this angle is called the dip or the inclination. If the vertical plane in which the needle moves is not that containing the magnetic meridian, the angle is always greater, and when the plane of movement lies magnetic east and west, the dipping needle will point vertically downwards, because in this plane the vertical direction is the one which most nearly corresponds with the actual direction of the lines of magnetic force. It should be remembered that, before magnetisation, the dipping needle is balanced as perfectly as possible on its pivots, so that the whole of the "dip" shall be due to magnetic forces only. In the plane of the meridian, as we have already remarked, the dipping needle lies along the terrestrial lines of force.

The value of the dip varies with the position of the place of observation, and to determine it accurately, a needle is used which is more elaborately mounted than that shown in Fig. 54.

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[1] See *Philsophical Transactions*, 1890. Section A.

A simple form of the "dip circle," as it is called, is illustrated in Fig. 61. A long magnetised needle, *a b*, is mounted so as to be free to turn in a vertical plane round a horizontal axis, *m*, and its position is read off on the vertical circle K_2. The frame containing the needle with its pivots and circle can be rotated about a vertical axis, and its angular position read off on the horizontal circle K_1, by means of the vernier *n*. Finally the whole instrument is mounted on levelling screws, and when used is carefully levelled by the aid of the spirit-level seen immediately beneath the vertical circle.

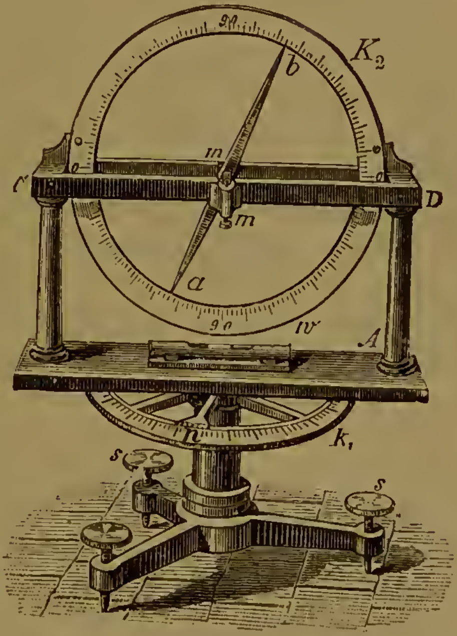

Fig. 61.--Dip Circle.

By using such an instrument, the values of the "dip" can be found at various points on the surface, and the results plotted down on the maps in a similar way to that adopted for the varying values of the "declination." That is, places where the "dip" is the same are joined by a line marked with the value of the dip, and called an *Isoclinic*. These lines are, as a rule, at right angles to the isogonals, and are subject to similar irregularities. The line of no inclination along which the needle sets horizontally lies irregularly in the neighbourhood of the equator.

As we recede from this line, the dip increases; in the northern hemisphere the north-seeking end of the needle dips downwards, and in the southern hemisphere the south-seeking end. At the magnetic poles the dipping needle stands vertical in all planes. The dipping needle when properly adjusted *shows the actual direction of the lines of force of the Earth's Field* at the place of observation.

Magnetic Force.—The complete knowledge of the magnetic field of the earth at any point involves the determination of the *magnitude* as well as the *direction* of the magnetic force at that point. This determination of the magnitude of the earth's magnetic force, or, as it is sometimes called, the "intensity of terrestrial magnetism," can be effected in several ways. All these, however, are somewhat complicated, and a full description of any one of them would lead us beyond the limits laid down for this book. A method frequently used in England consists in first observing the effect of a stationary magnet on a little compass-needle controlled by the earth's field, and afterwards suspending the former magnet horizontally by a thread, and noting the time of an oscillation when under the action of the earth alone. The first observation gives the *ratio* of the *magnetic moment* of the deflecting magnet to the *magnetic force* of the earth; the second gives a result depending upon the product of these two quantities. By combining the two results, therefore, the values of both quantities can be calculated. Like the declination and the dip, the value of the magnetic force varies from place to place.

The Magnetic Elements.—The three quantities to which we have just referred, namely :—

(1) The declination,
(2) The dip, or inclination,
(3) The magnetic force,

are usually known as the "magnetic elements," and the daily, or hourly, or even more frequent determination of them is one of the chief objects of the numerous magnetic observatories that are now scattered over the face of the globe. This is rendered necessary by the fact that not only are the values of each of them different in different places, but also because these values are themselves subject to rather complicated variations from year to year, from day to day, and even from one hour to another. Indeed, the direction in which a compass-needle points, and which in early days was regarded as so fixed that its invariability became symbolical of constancy, turns out on a more exact and fuller investigation to be one of the most variable factors in the whole range of physical quantities. It and its companion elements are in a continual state of ebb and flow, under the action of laws, the full meaning of which we are yet far from understanding. For convenience these variations may be grouped in four categories :—(1) secular, (2) annual, (3) diurnal, (4) irregular—which we shall briefly consider.

Variations of the Elements.—(1) *Secular.* The values of the declination and inclination at any place at which there are records going back two or three hundred years, are very different to-day from what they were when first accurate measurements were taken. Thus, observations made in London about the year 1580 gave the declination as 11° 17′ *East*, whereas it is now 17° 41′·9 *West;* and the inclination, which was then 71° 50′, is now only 67° 31′·2. In the interval the declination has been as great as 24° 38′ West (in 1818), and is now slowly diminishing. In 1657 there was no declination, the needle in London then pointing due north. Similarly the inclination has been as high as 74° 42′ (in 1720), and is now diminishing. The following table gives a few of the values that have been recorded from time to time :—

TABLE IV.—SECULAR MAGNETIC VARIATION IN LONDON.

Year.	Declination.	Inclination.
1576	11° 17′ East	71° 50′
1600	—	72°
1622	6° 12′ ,,	—
1657	0° 0′	73° 30′
1692	6° 0′ West	—
1720	13° 0′	74° 42′
1748	17° 40′	—
1800	24° 6′	72° 8′
1818	24° 38′	70° 30′
1830	24° 2′	69° 30′
1860	21° 40′	68° 19′
1884	18° 7′·6	67° 30′
1891	17° 41′·9	67° 31′·2

An examination of this table, which is similar to the tables for other places though the actual values are different, reveals two points of interest. First, that the changes are of the nature of an oscillation to and fro about some mean position; and, secondly, that the period of a complete oscillation is so long that, although the table extends over more than three hundred years, the earliest values have not yet recurred. If we assume that the geographical meridian marks the centre of the oscillation, then a quarter-swing of the declination occupied 161 years (from 1657 to 1818), which gives 664 years for the complete period. The assumption, though probable, must not, however, be regarded as proved. These changes have been usually explained as being caused by a slow rotation of the magnetic pole round the geographical pole. But recent comparisons by Captain Creale of the magnetic maps of the world for 1840 and 1880 show that there is no evidence of the motion of the magnetic poles. The proximate cause of the variation is still a mystery.

(2) *Annual Variations.*—Superposed upon the above long-period changes, there are much smaller changes, which

go through a complete cycle in the course of a year, and seem to depend upon the position of the sun with respect to the equator. Thus in the northern hemisphere the declination is at a *maximum* distance, to the *East* of its average value for the year, in the month of February, whilst in the months of July, August, or September (according to the position of the observing-station), it is a *maximum* distance to the *West* of the average value. The changes in the southern hemisphere are similar, but opposite in direction. The variation is small, seldom exceeding one or two minutes of arc from the mean value for the year; nevertheless it is quite distinct and periodic.

(3) *Diurnal Variations.*—The hourly position of the sun with respect to the place of observation also affects the magnetic elements. It will, perhaps, suffice to briefly describe the effect on the declination in Europe. At 9.45 a.m. and 6 p.m. (local time) the compass-needle is in its mean position for the whole day, but between these hours in the day-time it lies to the West of the mean position, and in the night-time to the East. The needle lies furthest to the West about 1.0 p.m.; the time of greatest Easterly variation is more variable, changing from about 10 p.m. in winter to 7 a.m. in summer. The average variation for a single day is about 9·5 minutes of arc, but is greater in summer and less in winter.

As we have pointed out, both the annual and the diurnal variations are solar effects, and it is interesting to note in passing, that a small set of variations due to the moon has also been traced by Kreil; the discussion of these would, however, lead us beyond the limits at our disposal.

(4) *Irregular Variations.*—In addition to the above regular variations of the magnetic elements, there occur from time to time sudden disturbances, whose magnitude and direction have not yet been referred to any regular laws. The fact, however, that they are absolutely simultaneous

at very distant stations seems to indicate that they are due to influences outside the earth. Attempts have been made to ascertain whether these "magnetic storms," as they are called, follow any definite law with regard to the frequency and time of their appearance, but a discussion of some of the tentative results obtained would, we fear, be wearisome to our readers. It is, however, of interest to note that the appearance of an aurora is usually accompanied by a magnetic storm.

Electro-Magnetism.

The discovery of Oersted (*see* page 15) in 1820 that a conductor carrying a steady electric current affected a magnetic needle placed near it, was soon followed by other discoveries which proved that the current-carrying conductor had magnetising properties. It is to these magnetising properties that we propose to refer particularly now, leaving over the general consideration of the magnetic action of the current to a subsequent section.

In 1820, Arago, guided by Ampère's theory, which had just been published, showed that a steel needle could be magnetised by placing it inside a spirally twisted wire along which a current was flowing. He also found that if the discharge of a Leyden jar was passed through the spiral, the enclosed needle was magnetised. Davy, almost simultaneously (in November, 1820), observed the same effects, and also that if a wire carrying the current of a large battery were dipped in iron filings, the filings hung in chains around it.

Of the experimenters above referred to, Ampère's work was singularly complete, both experimentally and mathematically. Guided by Oersted's discovery, he inferred that if a steady current[1] mechanically affected a magnet, then a magnet must mechanically affect a steady current so mounted as to be free to move. This he showed was actually the case. He then passed further, and showed by a series of masterly experiments that there is a mechanical action between steady currents placed near one another. With this latter discovery we are not just now concerned, but a particular case of the previous work is interesting. Since the earth is a big magnet, it should act mechanically upon a freely suspended wire carrying a current. This is best shown where the wire is twisted up into a spiral tube, or *solenoid*, as in Fig. 62. The arrow-heads are intended to indicate the direction of the current, and those placed on the spirals are supposed to be on the front parts of the wires. If a spectator were to stand at the end *S* of the solenoid and look along the axis, all these currents would appear to him to be circulating round the axis in a *clockwise* direction. The solenoid is so constructed that it can be suspended from the mercury-cups *A* and *B*, which are connected to the positive and negative poles of a battery by the wires *C* and *Z*. This leaves it free to rotate round the vertical line through *A* and *B*, and it is found that, if there be no magnets near, the axis of the solenoid will set in

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[1] The word "current" is here used briefly for "conductor carrying a current."

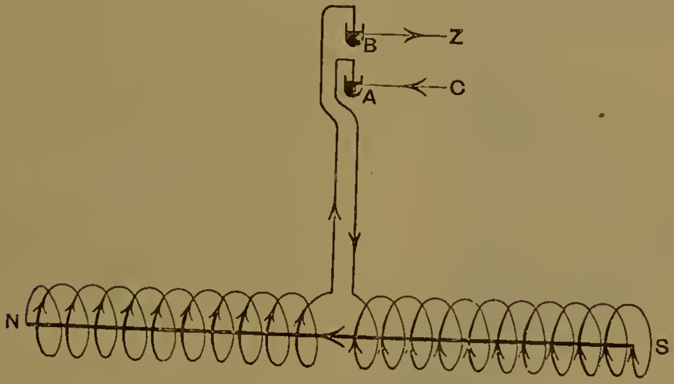

Fig. 62.—Suspended Solenoid.

the magnetic meridian with the end *N* pointing towards the north magnetic pole. The solenoid with its current behaves just like an horizontal compass-needle. In fact it has all the properties of a rather feeble magnet. Thus, if the north pole of a bar magnet be brought near *N* (Fig. 63), the latter will be repelled; whilst it will be attracted by the south pole of the bar magnet.

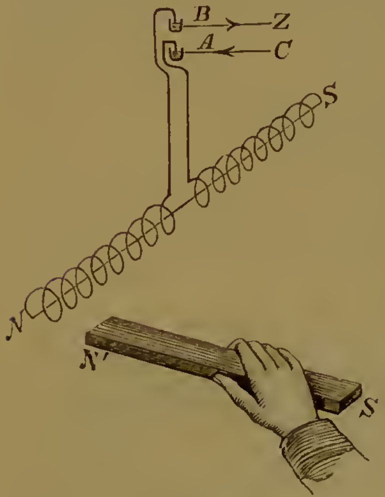

Fig. 63.—Solenoid repelled by a Magnet.

It is very important to remember the relation between the direction of the current in the spirals and the magnetic actions manifested at the ends of the solenoid. Many mnemonical rules have been given for this purpose, but it will suffice if we quote the particular one of these which we think is most easily remembered, and which is applicable to a great number of cases. It is known as the "corkscrew rule," and is as follows:—If the *current* be supposed to circulate in the *spirals* of a corkscrew in the direction of *rotation* of the screw, the direction of the *magnetic lines along the axis* will be that of the *line of advance* of the corkscrew. Now the magnetic lines emerge from a magnet at the north pole, and therefore in the above case the *forward-moving* end of the screw (whether front or back) will act as north pole. The rule is illustrated in Fig. 64,[1] in which little arrows show the direction of the current. If the corkscrew be turned in this direction it will move downwards, and the rule tells us that this is the direction of the magnetic lines along the axis; consequently if a piece of iron be placed along the axis as shown, it will be magnetised so that its lower end is a north-seeking pole.

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[1] Taken from Prof. Ayrton's "Practical Electricity."

The discovery that in the magnetising action of a current, which could be started, stopped, or reversed at pleasure, there lay the power of making or unmaking a magnet, or reversing its polarity as often as might be desired, was due to William Sturgeon, who also showed that such magnets could be made much more powerful than steel magnets of the same size and weight. This latter effect was produced by placing inside the spirally wound conductor large *rods* or *bars* of *soft iron*, instead of the *steel needles* employed by Arago and Davy. We have already seen that soft iron is capable of being highly magnetised by induction when placed in a magnetic field, but that when it is removed from the field (or the field from it) it retains very little trace of permanent magnetisation. Now, as we have just seen, an

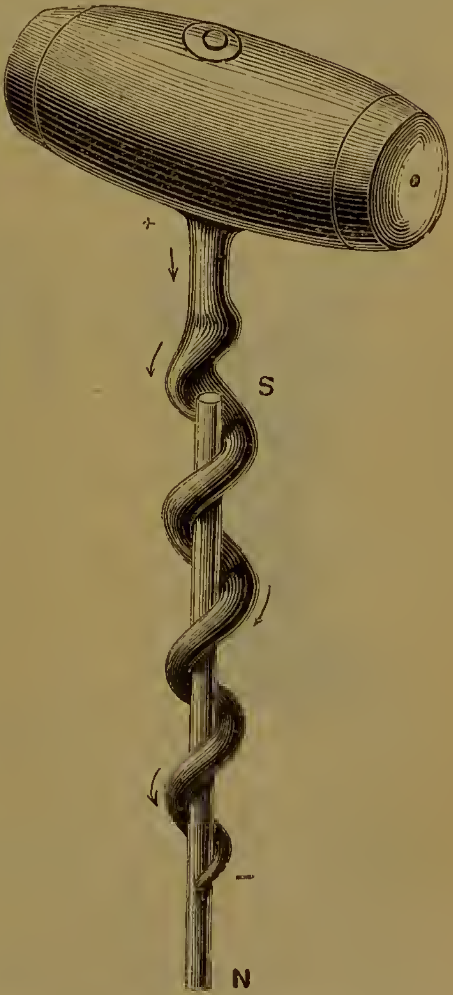

Fig. 64.—Corkscrew rule for Relation between Current and Magnetic Flux.

electric current flowing round the coils of a spirally wound conductor sets up a magnetic field in the enclosed and surrounding space. When the current is stopped, the magnetic field disappears. If, therefore, a bar or rod of *soft wrought iron* be placed in this field, this bar will be a magnet as long as the current flows, but will retain very little evidence of magnetisation when the current is turned off.

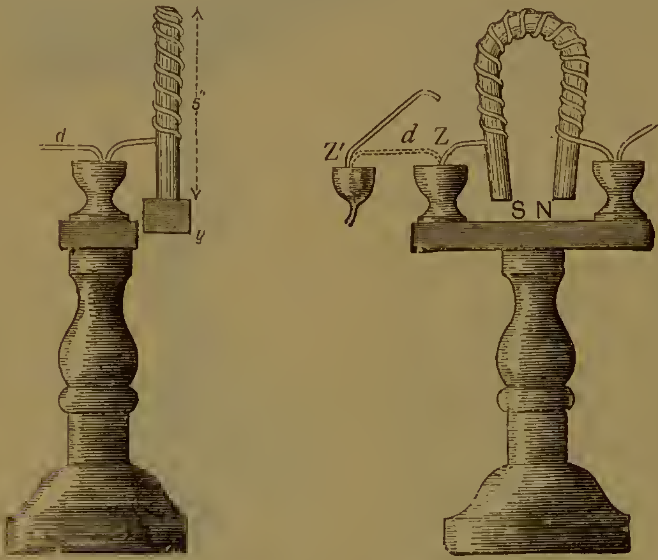

Fig. 65. Sturgeon's Electro-magnet. Fig. 66.

In a paper published in the *Transactions of the Society of Arts* for 1825, Sturgeon describes two electromagnets which he exhibited at a meeting of the Society. One of these, of which front and side views are shown in Figs. 65 and 66,[1] consisted of a bar of iron one foot long and half an inch in diameter, bent into the shape of a horseshoe. This bar was varnished and then overwound with a spiral of stout uncovered copper wire, the ends of which dipped into the two wooden cups *Z* and *C* containing mercury. Near the cup *Z* was a similar cup *Z′*, into which one of the wires from the battery dippped, the other wire from the battery being led into the cup *C*. Sturgeon used a special form of battery, similar to Hare's deflagrator (p. 36). On joining the cups *Z* and *Z′* with the wire *d*, the circuit of the battery was completed, and a fairly large current flowed round the coils of the spiral; it was then found that a total weight of nine pounds could be sustained by the traction of the poles N S of the horse-shoe. As the iron of the magnet only weighed about *seven ounces*, this was much in excess of the weight that could be sustained by any magnet of equal mass previously made. In the side view (Fig. 65) the poles are represented as sustaining a piece of iron, *y*. If the current from the battery enters the spiral from the cup *C*, then it will flow in a counter-clockwise direction round the iron as seen from N, and, consequently, according to the rule already given, the end *N* of the coil will be a north magnetic pole, the other end being south. Sturgeon remarks that the polarity of the iron can be reversed, either by winding the spirals round in the opposite direction, or, more simply, by reversing the connections of the magnetising spiral with the battery by interchanging the battery wires that dip into the cups *C* and *Z′*.

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[1] For Figs. 65, 66, and 67, taken from the *Transactions of the Society of Arts* for 1825, I am indebted to Dr. Silvanus P. Thompson.

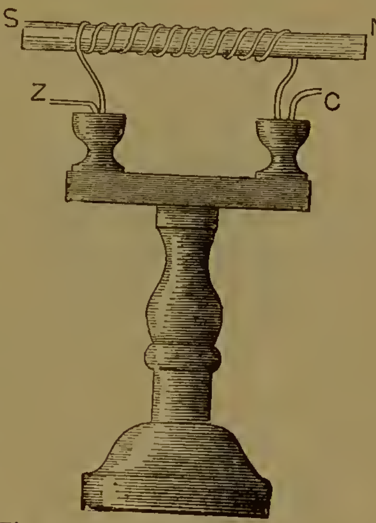

Fig. 67.—Sturgeon's Straight Electro-magnet.

For convenience of slipping bars of iron or steel into a magnetising spiral, Sturgeon mounted a straight solenoid (Fig. 67) in a similar manner. When a current flows in this spiral, it "communicates magnetism to hardened steel bars as soon as they are put in, and renders soft iron within it magnetic during the time of action." The letters *N* and *S* refer to the polarity produced by a current entering at *C* and leaving at *Z*.

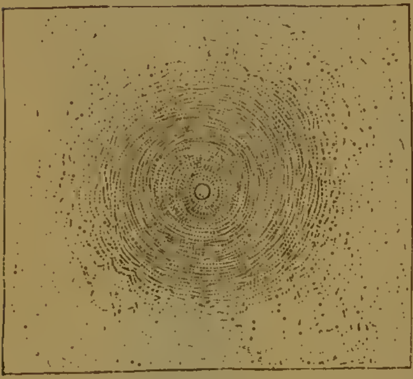

Fig. 68.—Magnetic Curves round a Straight Current.

In order to understand the foregoing actions more clearly, it is necessary to have some idea of the kind of magnetic field, as specified by the direction and number of lines of force, which exists in the neighbourhood of a conductor carrying a current. These lines were first mapped out by Faraday in the manner already described with reference to permanent magnets, and the following figures are taken from one of his papers, dated 1851, in which he sums up many of the results of his work during the preceding twenty years.

Taking the simplest case of all, that of a straight conductor carrying a current, Fig. 68 shows the magnetic field as mapped out by iron filings spread on a plane *perpendicular* to the current. The wire carrying the current is supposed to pass at right angles through the paper, and the filings are seen to arrange themselves in paths which are circular with the wire as a centre. More careful experiment shows that the lines are true *concentric circles*, the common centre being the intersection of the axis of the wire with the paper. The connection between the direction of the current and the direction of the lines of force can be remembered by another application of the corkscrew rule already quoted. In this case the *line of advance* of the corkscrew represents the *current*, and the direction of *rotation* represents the *positive direction* of the encircling *lines of force*. Thus in Fig. 68, if the current be passing vertically *downwards* through the paper, the positive direction of the circular lines of force is a right-handed, or *clockwise one*. It should be noticed that each line is a *closed curve*, completed entirely *through the air*. In this respect it differs from the lines of force of permanent steel magnets, each of which in some part of its course passes through the material of the magnet. *No magnetic poles*, therefore, are set up by these lines, since they nowhere pass from magnetic to non-magnetic material, or *vice versâ*.

If a ring of iron were now slipped over the wire so as to lie concentrically with these circles in the plane of the paper, it is evident from what we have already said (page 116) that many lines of force would be gathered up into the iron, and would flow through it in the same way as through the air, only in greater numbers. This ring could therefore become highly magnetised, but would not show any external signs of magnetisation. It would have *no poles*, since its lines of force would flow entirely through the iron. That it really is magnetised can be proved by using steel instead of iron. In this case, if the current be stopped, the steel will retain the impressed magnetisation because of its molecular rigidity. Let the ring now be divided into two semicircular pieces by transverse cuts; each of these when separated will be found to be magnetised with strong poles at the planes of section. But before the ring is cut, it will have no more effect upon a compass-needle in its neighbourhood than it had before it was magnetised.

Consider now the effect of bending the wire, carrying with it its lines of force, into a single circular loop. Follow out the corkscrew rule, and it will not be difficult to see that *inside* the loop all the lines must be flowing in the *same direction* from one side to the other of the plane of the loop. A few of these lines for a current circulating in a clockwise direction round the loop are shown in Fig. 69. Because of the apparent lateral repulsion of lines of force for one another, and the crowding together of the lines inside the loop, the curves surrounding the wire will no longer be concentric circles, but will be distorted.] Each line, however, still passes completely round the loop.

These lines can be shown by iron filings; the card

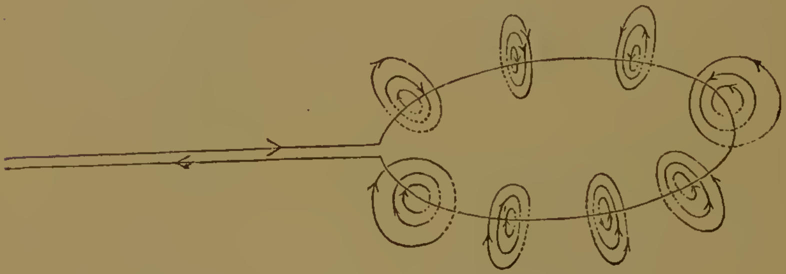

Fig. 69.—Lines of Force of a Circular Loop.

should be placed so as to cut the loop at right angles through a diameter. On sprinkling with iron filings, and tapping in the usual way, the effect produced is that shown in Fig. 70. The wire of the loop passes through the card at *a* and *b*, and if the current comes upwards at *a*, and goes downwards at *b*, the *direction* of the lines of force between *a* and *b* is that shown by the small arrow.

Let us carry the development a step further. Suppose now that several of these loops of the same diameter are placed side by side so as to have a common axis, much in the same way that a series of similar coins may be arranged in a *rouleau*. Suppose also that, looking along the common axis, all the currents in the separate loops revolve round the axis in the same direction, either all clockwise or all counter-clockwise. In the plane of each loop, and inside the loop, the magnetic lines which belong to it will be parallel to the axis, and all the lines of the different loops will be trending in the same direction. The lines will therefore blend together just as the lines of two bar magnets set as in Fig. 49 blend together to give the field there depicted, instead of each pursuing its own course unaltered, as in Fig. 47. We thus get the field shown in Fig. 71, which is also taken from Faraday. The arrangement of loops that we have just described is that of the loops of a solenoid, and in the figure the filings are spread upon a card containing the axis of the solenoid, and whose plane therefore cuts through the wires. The wires are seen in section at *a a a* and *b b b*, and it will be noticed that between the lines of the wires the field is very uniform, the filings lying in lines parallel to the axis. If the current be supposed to be coming upwards in the parts of the wire marked *a*, and going downwards

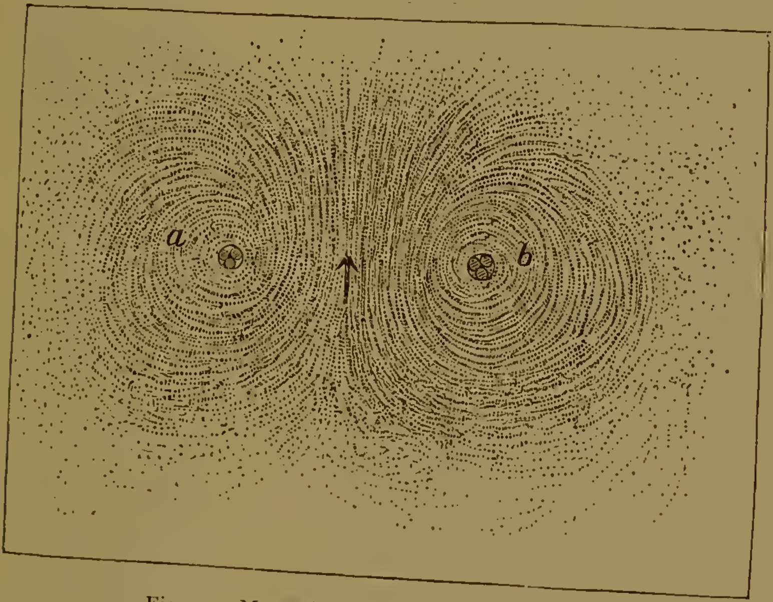

Fig. 70.—Magnetic Curves of a Circular Loop.

in the parts marked *b*, the direction of this *internal* field will be from left to right as shown by the small arrow. In this case only a part of the external field is shown by Faraday, but it is easily seen that the lines of force are setting out from the end of the solenoid, exactly in the same way that they set out from the end of a single-bar magnet.

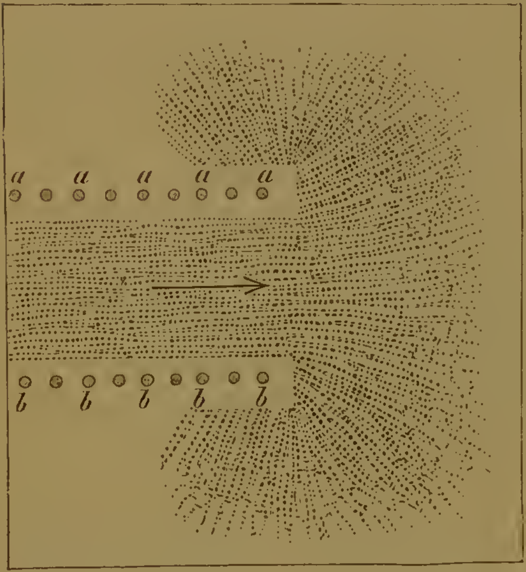

Fig. 71.—Magnetic Curves of a Solenoid.

Direction of Magnetising Force of a Coil.—The result is that if we have a cylindric coil of wire (such as is seen in Figs. 62 and 63) carrying a current which when regarded from one end of the coil circulates round the axis in a clockwise direction, then the lines of force due to that current pass down inside the coil in a direction passing away from us. An iron core inside the coil (as already pointed out on page 140) will therefore be magnetised so that its so-called South pole is towards us, since if we faced the south pole of a bar magnet, the lines of force would run from us *through the iron* of the magnet in the same way. Of course if the current circulates counter-clockwise, the lines are running towards us through the coil, and the nearest end of an inserted core becomes a North pole. These relations are shown in Fig. 72, where the direction of circulation of the current is shown by the arrows on the circles, and the name of the pole nearest the observer is expressed by the letter N or S. The corkscrew rule enables one to easily remember the facts. In this case if the direction of circulation of the *current* be given by the *rotation* of the corkscrew, the *line of advance* of the corkscrew gives the direction of the *lines of force* along the axis of the solenoid. One additional remark may be made. Whether the wire of the solenoid be wound in right-handed or left-handed spirals is a matter of indifference; the important point to notice is the *direction of circulation* of the current as seen from one end. If that direction be *clockwise*, then the observer is looking at the *South* pole, whether the spirals in which the current is flowing be right or left-handedly wound.

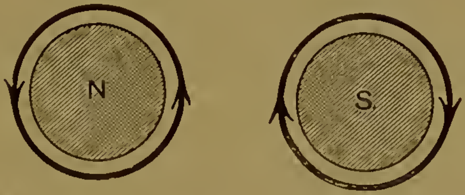

Fig. 72.—Relation between Current Circulation and Poles of Core.

We have dwelt thus fully upon the relation between a current and its lines of force, because a clear understanding of these simple cases will enable the reader to follow readily many applications which at first sight may seem intricate.

Magnitude of Magnetising Force of a Coil.—Very soon after the discovery of the magnetising effect of a coil, it was observed that this effect depended upon the magnitude or *quantity*, as it was then called, of the current. But the honour of first perceiving the important factors upon which the magnetising force really depends belongs to Joseph Henry, of New York, who published his early experiments in 1831.[1] This was before Ohm's law, which introduced simple ideas into the relations between current and electromotive force, had become widely known and generally used in the scientific world, and Henry's results are not embodied in the precise form now usually employed. What he discovered was that a weak current circulating many times round an iron core could produce the same magnetising effect as a strong current circulating round it a few times. In other words he found that the product of the *current* by the *number of turns* in the solenoid is a measure of its magnetising force, or rather of its *magnetomotive force.* If the current be measured in ampères, this product is now usually spoken of as the *ampère-turns.* Thus if a coil be carrying a current, we may say briefly that its *magnetomotive force is proportional to the ampère-turns.*

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[1] Silliman's *American Journal of Science*, 1831.

This discovery of Henry's was of enormous importance to the young science of telegraphy, then beginning to attract the attention of practical scientists. It showed how the weak currents, which at that time were the only currents that could be transmitted to any distance, could be utilised to make effective working electro-magnets, and thus produce signals at a distant station.

Exact experiments have fully proved the truth of the law just enunciated. A numerical example will perhaps make its meaning somewhat clearer. Thus it is found by experiment that the magnetomotive force of a current of 10 ampères circulating in a spiral of 12 turns, is exactly the same as that of a current of 1 ampère in a spiral of 120 turns, or that of a current of $\frac{1}{100}$ ampère in a spiral of 12,000 turns. In each case the ampère-turns are 120. That the effect produced by this Magnetomotive Force should also be the same in each case, further conditions must be fulfilled. These are that the coils should be similar, of equal volume, length, diameter, &c., and that the cores and surrounding medium should be magnetically identical. The analogy with the case of a galvanic battery is very close. A battery of a certain *E.M.F.* will drive a certain *current* round a circuit of a particular *resistance.* Similarly a coil with a certain *magnetomotive force* (*M.M.F.*) measured in ampère-turns will cause a certain number of *lines of force* to pass through a core and surrounding medium of a particular *reluctance.* If the reluctance is diminished, the number of lines of force is increased, and *vice versâ.*

The conditions for small reluctance are exactly similar to those for small resistance in the electric circuit. In the latter case the material of the circuit should be of high conductivity, large sectional area, and short in length. In the magnetic case the medium through which the lines of force have to pass should be of high permeability, large sectional area perpendicular to the lines of force, and short in length. The first of these conditions (high permeability) points to the providing of as much well-annealed soft iron for the lines to pass through as the design and purpose of the electro-magnet will permit. In one sense the magnetic circuit has an advantage over the electric circuit, in that the *whole* space round the coil producing the *M.M.F.* is permeable to lines of force, and by its mere bulk and great sectional area contributes to a lowering of the reluctance. This is, however, accompanied by certain disadvantages, the consideration of which we shall postpone till we deal with the numerical relations later on (p. 323).

Magnetic Permeability.—As the quality or permeability of the iron is so important in the construction of electro-magnets, it is necessary to know something of how different kinds of iron behave when subjected to magnetising forces. On page 101 we have already pointed out the general behaviour of various kinds of iron and steel in this respect. We must now refer to the experimental data a little more closely. And first a definite meaning must be attached to the otherwise somewhat vague term *permeability.*

When considering by the help of iron filings the effect on the lines of force of placing a piece of iron in a magnetic field, we found (*see* Figs. 52 and 53) that the appearances were such as to suggest that the lines found it easier to get through the iron than through the air. Now, when the field is due to the magnetic effect of a current, we find that this is still the case, and, in addition, that the presence of the iron increases the total number of lines[1] set up by the current. This multiplying power of the iron is a measure of its permeability. If no iron is present, then we get a certain magnetic field which at a given place contains a certain number (H) of lines per square centimetre of cross-section. If now the air or non-magnetic material is replaced by iron, a greater number of lines (B) per square centimetre passes through the same space. The original number of lines has been multiplied, and the numerical factor which expresses the ratio between B and H is the measure of the permeability. This multiplier is usually denoted by the Greek letter μ, and we have the simple numerical relation that B is μ times H, or

$$\mathsf{B} = \mu \, \mathsf{H}.$$

The value of μ varies very greatly in different specimens of iron and under different circumstances. It may be as high as 5,000, or as low as 20 or less. Methods of measuring it will be briefly described in Part II., Chapter VIII.

Magnetic Saturation.—Besides the variations in the value of μ in different kinds of iron, it also varies in the same piece of iron according to the *strength of the magnetising field*, and to the previous *magnetic history* of the iron.

The corresponding values of H and B for various kinds of iron and steel are shown graphically and numerically in

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[1] *See* page 323 for the exact meaning of the phrase "total number of lines."

Fig. 73, where the values of H in certain units are marked on the horizontal scale and the corresponding values of B in the same units are marked on the vertical scale. The data are taken from some of Ewing's experiments.

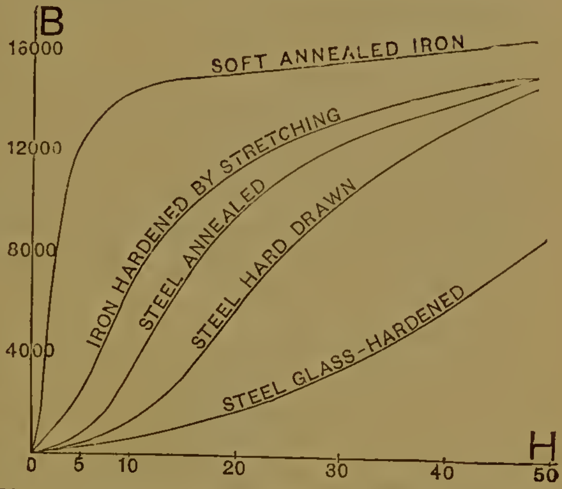

Fig. 73.—Curves of Magnetisation of Different Materials.

For weak magnetising fields the magnetic flux B produced in the iron by a given field H is very nearly proportional to H; in other words, the value of μ is nearly constant, and any increase in H produces a corresponding increase in B. But as the strength of the magnetising field is increased, a point is reached sooner or later at which the value of B, though still increasing, increases more slowly than before, and therefore the value of μ diminishes. This continues for a time, until usually the rate of increase of B as compared with H diminishes to another

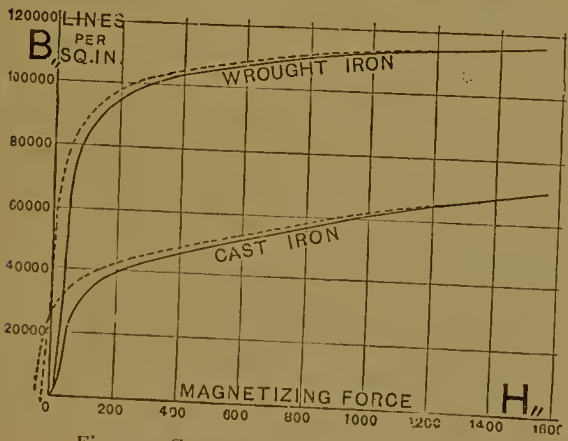

Fig. 74.—Curves of Magnetisation of Iron.

steady value much less than the first one, and large increases of magnetising force only give small increments o magnetisation.

This is especially marked in the curve for wrought iron It rises very rapidly at first, then bends over, and finally becomes nearly horizontal. In this last stage, when large changes in the magnetising force are required to produce small changes in the magnetic flux, the iron is said to be approaching *saturation*. In such cases, although more lines could be obtained by using more powerful magnetomotive forces, it does not pay practically to do so, because of the much more rapid increase of the wasteful heat in the magnetising coils. Some similar curves obtained by Hopkinson for wrought and cast iron are given in Fig. 74. In these curves the values of **B** and **H** are given as the number of lines per *square inch*, instead of per square centimetre.

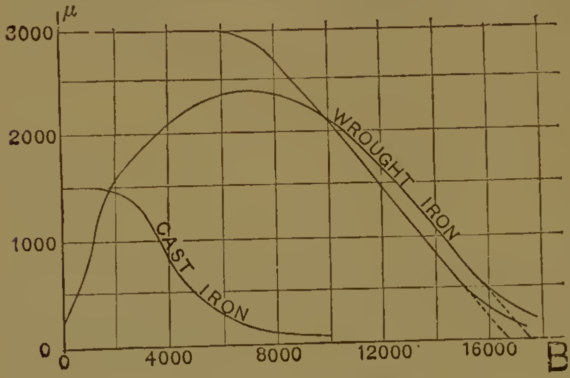

Fig. 75.—Curves of Permeability.

Instead of plotting curves which graphically depict the connection between **B** and **H**, we may exhibit in curves the connection between μ and **B**. This is done in Fig. 75, in which the values of **B** are measured on the horizontal scale, and the corresponding values of μ on the vertical scale. The rapid diminution of the permeability with the increase of the magnetic flux is very marked, and also the great difference in permeability between cast and wrought iron.

Magnetic Hysteresis.—We must notice briefly one other magnetic property of iron, called by Professor Ewing *hysteresis* (or *lag*). It is found that the value of **B** corresponding to a given value of **H** depends upon the previous magnetic history of the iron. Iron appears to have a *magnetic memory*, and to retain impressions of previous magnetic states. The facts are shown graphically in Fig. 76 (taken from some of Ewing's experiments), which gives the curves obtained from two specimens, one of wrought iron, the other of steel. Each curve forms a closed loop, but the steel loop is much wider than the iron one. Commencing with a large magnetising force, we have the point *a* (on the steel curve); as the magnetising force is diminished to *zero*, the value of **B** only falls to *b* (= 60,000), and **H** has to be *reversed* before **B** falls to zero at the point *c*. Increasing the reversed value of **H**, we travel up to *d*, where the steel is nearly saturated in the opposite direction to the first. If now the reversed value of **H** be gradually diminished to zero, then changed over to its original direction, and increased up to its first value, we travel through the points *d*, *e*, and *f*, back to the starting-point *a*, and the loop is completed. At each point the value of **B** seems to retain traces of previous values; when the magnetomotive force is *diminishing*, the value of **B** is *higher* than it is for the corresponding value of **H** when **H** is *increasing*.

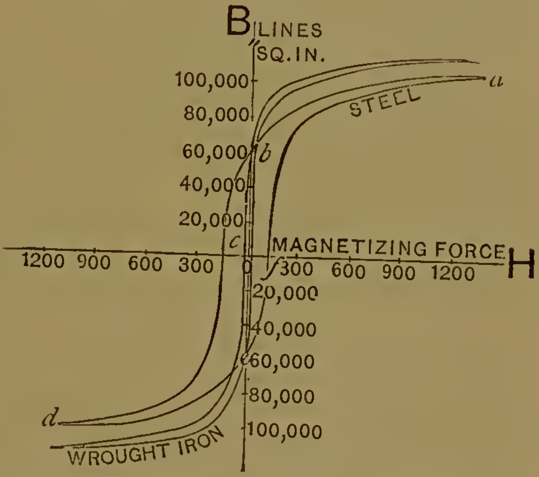

Fig. 76.—Curves of Magnetic Hysteresis.

The area of this loop for a complete cycle of magnetomotive force is very important wherever rapid reversals of magnetisation are employed, as in the armatures of dynamos, and in transformers, for it measures the energy wasted in each complete cycle of magnetisation. It should be noticed that the area of the wrought-iron loop is much less than that of the steel loop. The value oc or of, through which **H** has to be reversed in order to bring down the magnetic flux to zero, is regarded by Dr. Hopkinson as the true measure of the so-called *coercive* or *coercitive force*.

Forms of Electro-magnets.—Returning to the electro-magnet, we find that the essential parts are the *electric conductor*, usually in the form of a coil, for the purpose of carrying the electric current, and thereby setting up a magneto-motive force, and the *magnetic circuit*, through which lines of force are to pass. In all electro-magnets, properly so-called, some portion of the magnetic circuit or path for the magnetic lines consists of iron or other highly magnetisable material: if a portion of this iron is free to move, as in the vibrating armature of an electric bell, then as a rule motion will be set up when the current passes, and mechanical work of various kinds may be performed.

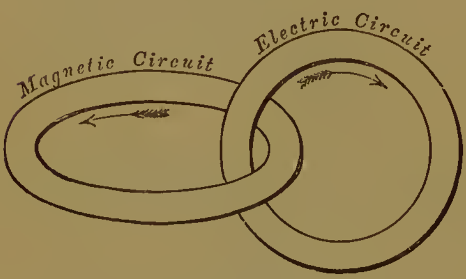

Fig. 77.—Relative Positions of Electric and Magnetic Circuits.

With regard to the relative position of the two essential parts, the only necessary condition is that they should mutually pass through one another. Thus in Sturgeon's Electro-magnet (Fig. 67), all the magnetic lines of the magnet pass through the copper spirals, and *vice versâ* the copper spirals pass through every loop formed by the magnetic lines of force. This is still more clearly seen in Fig. 70 (page 147), which shows the magnetic field set up by a single loop; moreover in this figure the relative positions of the two intersecting curves of current and lines of force are depicted. The relative position may be briefly described as the same as that of two *closed loops* (Fig. 77) of any shape, one of which is threaded through the other, and consequently the latter must also be threaded through the former. As the essential relative position of the electric and magnetic circuits is thus very simple, it is obvious that it can be fulfilled in almost an infinite variety of ways; and as a matter of fact the number of different forms of electro-magnets that have been designed and invented is very great. But although theoretically it is only necessary to fulfil the above condition to get *an* electro-magnet, yet the particular purpose for which the electro-magnet is required, and the particular work it has to do, have to be very carefully taken into account if moderate efficiency is to be attained. In the next section we propose to take up more fully the quantitative relations involved, and throughout the remainder of the book we shall have frequently to describe electro-magnets of special design. We shall therefore be content at present with referring to a few forms interesting either historically or as types.

In Figs. 65 to 67 we have illustrated and referred to Sturgeon's early electro-magnets. Other electro-magnets of great historical interest are those used by Professor Henry in his early experiments, and some of which are shown in Fig. 78. This figure, for which the author is indebted to Professor S. P. Thompson, is copied from the *Scientific American* of December 11th, 1880, and represents Henry's electro-magnet as still preserved in Princeton College. The magnet is of the horseshoe type, and its *core*, as the internal iron of an electro-magnet is technically called, consists of a bar of soft iron, 20 inches long and 2 inches square, bent into the form of a horseshoe 9½ inches high. It weighed 21 lb., and its two ends or poles, properly surfaced, were connected by a lifter, technically called the *armature*, consisting of a piece of iron from the same bar filed perfectly flat. The wire to carry the electric current consisted of 540 feet of copper bell wire, wound on in nine separate coils of 60 feet each, with the ends brought out separately and marked, so that either the whole number or any desired combination of the various coils could be placed in

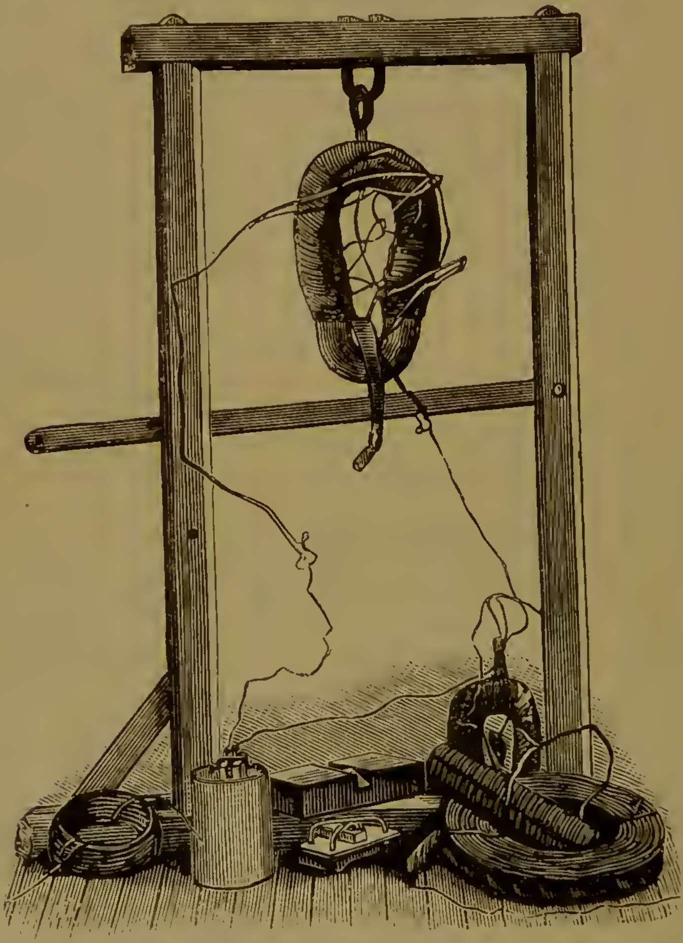

Fig. 78.—Henry's Electro-magnet

circuit with the battery. The magnet was suspended in a strong wooden frame, as shown, and below its poles was fixed a lever to which the armature was fastened by a loop. By means of weights sliding on this lever any desired force could be applied to the armature, and the pull necessary to detach it, with various combinations of the exciting coils, measured. Using the small copper-zinc single-fluid battery, shown at the foot of the frame, it was found that with one of the coils only in circuit the magnet was just able to support its 7-lb. armature, but as successive coils were added the force of detachment rose very rapidly at first, and afterwards more slowly, until with all the nine coils in circuit a force of 650 lb. weight was required to pull off the armature. Henry subsequently (in 1831) built a still larger electromagnet, which was capable of supporting a load on its armature of 2,063 lb. The other apparatus shown at the foot of the frame consists of a current-reverser, and some of the coils used in his experiments on secondary and tertiary induction currents, to which we shall refer later on. These were mostly constructed by Professor Henry's own hands.

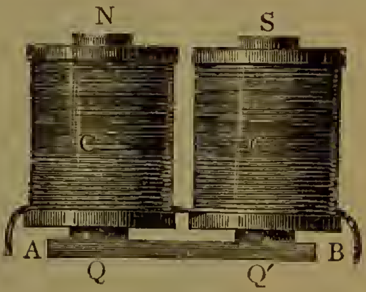

Fig. 79.—Two-Pole Electro-magnet.

Passing from historical forms, Fig. 79 shows the ordinary two-pole electro-magnet, which is the lineal descendant of the old horseshoe type. *C* and *C′* are the copper coils wound on separate bobbins, and connected together, by the wire seen passing over at the bottom, in such a way that when the two loose wires are joined to a current generator, such as a battery, the current as seen from the top circulates clockwise in one coil and counter-clockwise in the other. The result is that both coils tend to drive magnetic lines round the iron, $S\ Q'\ Q\ N$, in the same direction of circulation, and one of the poles N becomes a North pole, and the other S a South pole. The magnetic circuit consists of the two *cores* $N\ Q$ and $S\ Q'$, connected at the bottom by the *yoke* $A\ B$. All of these should be of good well-annealed soft iron. In the figure there is an air-gap from N to S in the magnetic circuit, but the pole-pieces and armature, which are usually placed either on or across $N S$ to diminish the reluctance of the circuit, are not shown, as their particular shape depends upon the purpose for which the magnet is required. One form of pole-pieces, used when very intense magnetic fields are required, is shown in Fig. 80. Here large blocks of soft iron are screwed firmly on to the top of the cores $N\ S$. These blocks are bored out horizontally, and in the holes are inserted the cylinders $e\ e_1$, which fit the holes tightly, but are finally held at any desired distance apart by

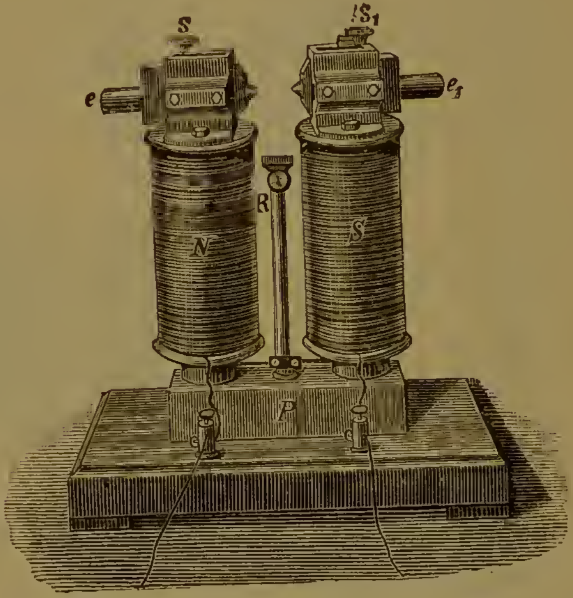

Fig. 80.—Electro-magnet for Intense Fields.

the clamping screws $s s_1$. The ends of these cylinders turned towards each other are pointed, so that the magnetic lines passing from one to the other find the most permeable path by crowding down to these points, thus lengthening the pathway in the more permeable iron, and shortening it in the less permeable air. It should be noticed also that the yoke *P* and the upright cores of the coils are exceptionally massive, so as to still further diminish the magnetic reluctance of the circuit. In this way a very intense field is produced in the air-space lying between the pointed ends of the cylinders $e\ e_1$.

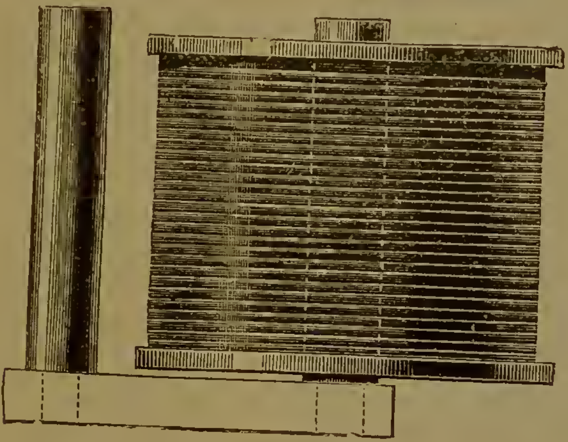

Fig. 81.—Club-footed Electro-magnet.

Still another form of this type of magnet is illustrated in Fig. 81, in which the shape of the magnetic circuit is the same as in Fig. 79, but the electric current is carried by the wires of a single coil, which is slipped over one of the cores only.

The change of shape from the original horseshoe form in all the above magnets has been made chiefly for convenience of manufacture, though partly for increased stability and compactness. It is much easier and cheaper to wind coils upon separate bobbins, and then slip them over the long straight cores, than to wind them on such a horseshoe as is shown in Fig. 78. As already remarked, the cores and yoke should be of well-annealed wrought iron; they should be carefully surfaced up, and fitted together where they join so as to diminish the magnetic reluctance of the gap; in fact, if high efficiency is desired, they should be forged in a single piece. But frequently in practice such high efficiency is not required, and the cores and yoke are made of cast-iron, cast in one piece; a diminution of the reluctance can in this case be secured by increasing the cross-section, and therefore the weight of the iron, which, it will be remembered, is *cæteris paribus* not so permeable to magnetic lines as wrought iron. By attending to these small details, electro-magnets can be manufactured in great numbers at a trifling cost; and for many purposes, where first cost is a primary consideration, they do their work as well as the most perfectly designed and expensively constructed electro-magnets. This is especially the case with electro-magnets for trembling-bells, indicators, etc., but when they have to be used in telegraphic instruments, telephones, or dynamo machines, the importance of good design becomes predominant. The advantages of the club-footed form (Fig. 81) are not very great: it is cheaper to make and more compact than the ordinary form, also its magnetic circuit is shorter, and therefore requires less magneto-motive force to set up a given magnetic flux. On the other hand, to obtain this magneto-motive force will require a greater expenditure of electric energy than if two coils were used with the same amount of copper wire upon them; for there will obviously, for the same resistance, be a less number of turns of wire on the stouter coil, and therefore a heavier current will be required to give the same number of ampère-turns (*see* page 150).

Another form of single-coil electro-magnet is shown in Fig. 82, where it will be noticed that the bobbin is enclosed in a closely-fitting outer cylinder of iron. This cylinder, which is magnetically connected to the lower end of the central core by a heavy circular yoke of iron (not shown in the figure), forms the return path for the magnetic lines set up in the core. Supposing a clockwise current in the coils, when looked at from above, the magnetic lines will pass vertically down the central core, spread out in all directions through the circular yoke at the bottom, and return upwards through the iron cylinder; the magnetic circuit is then completed through the air from the circular rim of the cylinder to the top of the central core. We thus have an annular or ring-shaped North pole (*N N*) surrounding an ordinary circular South pole *S*. The armature for such a magnet should of course be a circular disc, of the same diameter as the cylinder, and of sufficient thickness of iron.

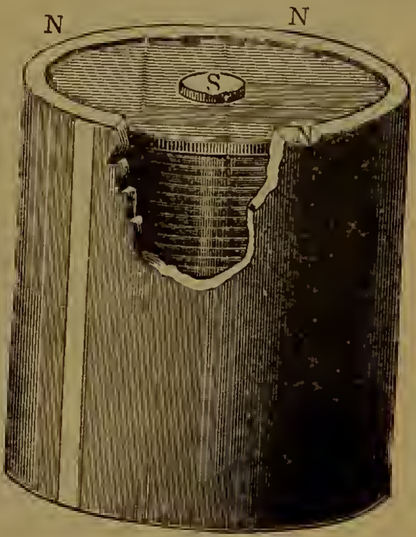

Fig. 82.—Iron-clad Electro-magnet.

A further modification, for very different purposes, of the two-pole electro-magnet is shown in Fig. 83, which represents the field magnets of a two-pole dynamo machine. Here the yoke *Y* is at the top and is very massive; the cores *C C* are also very thick, and the pole-pieces *N* and *S* correspondingly large. The object is to produce an intense field in the cylindric space between *N* and *S*, in which the spinning armature revolves, and it should be noticed how the compactness and massiveness of the magnetic circuit tend to reduce the reluctance. The magnet stands about four feet high, and in such large magnets the energy spent in maintaining the magnetising current is a serious item, and must be reduced to a minimum; hence the necessity for carefully following the indications of magnetic theory. The coils surrounding the cores *C C* are shown in section, and the feet, *a b*, on which the magnet rests, are of non-magnetic material, so as to cause more lines to pass through any iron placed in the cylindric space *A*.

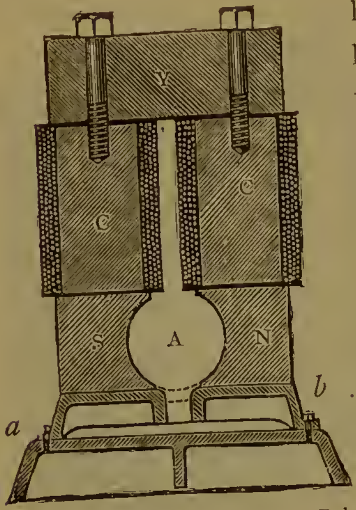

Fig. 83.—Field-Magnet of a Two-Pole Dynamo-Machine.

Fig. 84 illustrates a form of electro-magnet invented by Professor Hughes, and largely used, especially on the Continent, in his well-known printing telegraphs. It is of the two-pole type already referred to, with these differences: the body of the magnet consists of three or four similar and equal flat pieces of steel of horseshoe shape permanently magnetised and then clamped together. Such a magnet is known as a *compound permanent magnet*, and it is found that stronger magnets can be made in this way than with the same volume and shape of steel in the solid form. On the poles of this permanent magnet soft iron pole-pieces of the shape shown in the figure are screwed, and these are surrounded by the magnetising coils. The function of these coils is to increase and diminish the pull on the armature *a*, which works against the spring *s* shown in the side view on the left. By a series of exhaustive and patient researches, Professor Hughes discovered that this method of piling up the coils on the pole-pieces, gave far more *rapid working* than distributing them along the whole length of the magnet.

Thus in his printing telegraph the armature is moved by a small telegraphic current, lasting only about the one-hundredth part of a second.

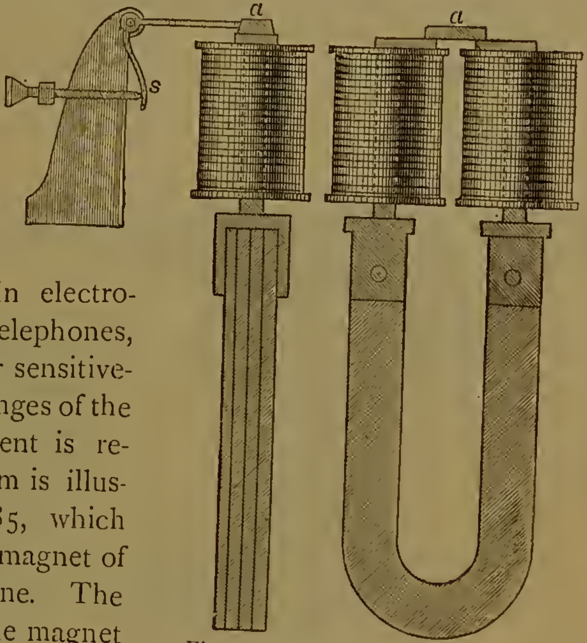

Fig. 84.—Hughes's Electro-magnet.

The same principle has been adopted in electro-magnets for telephones, where still greater sensitiveness to rapid changes of the magnetising current is required. One form is illustrated in Fig. 85, which shows the electro magnet of a Gower telephone. The yoke, *N O S*, of the magnet is semicircular, and the coils which are to receive the rapidly changing currents are seen piled on to the ends of the pole-pieces.

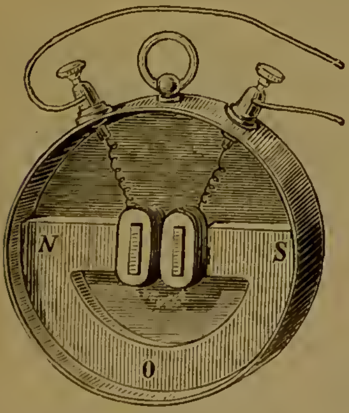

Fig. 85.—Electro-magnet of Gower Telephone.

Most of the electro-magnets hitherto described produce mechanical motion by drawing a movable armature up to their poles, but an entirely different way in which a magnetising solenoid can be used to produce such motion is shown in Fig. 86. This has been recently called by Dr. Thompson the Coil-and-Plunger Electro-magnet. The fact that a solenoid was able to attract into it a piece of soft iron was very early observed in the history of electro-magnetism, and was utilised in many early forms of electro-magnetic engines. The method of working can be demonstrated with the apparatus shown in the figure. A hollow solenoid *A* is

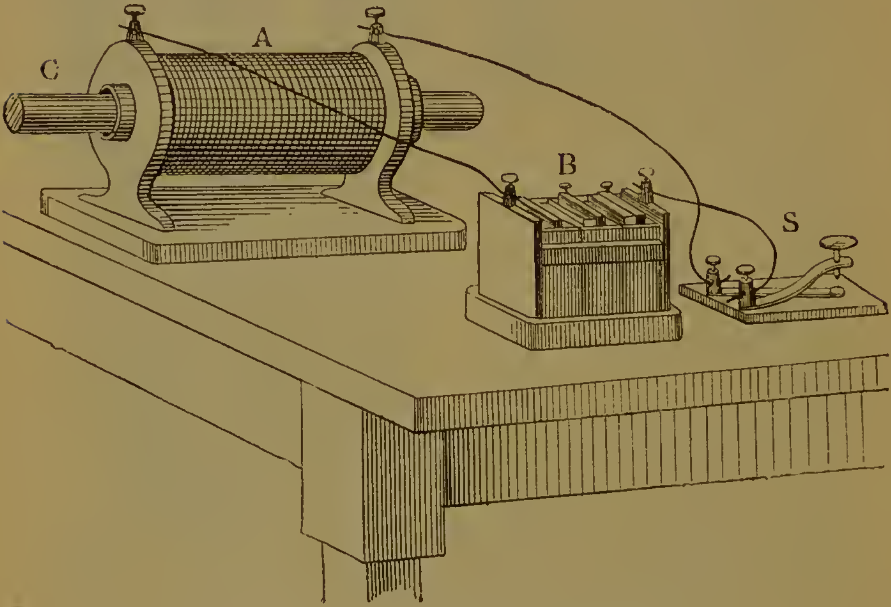

Fig. 86.—Coil and Plunger Electro-magnet.

joined to a battery *B*, and a key *S*; the soft iron core of the solenoid can be withdrawn. Let it be withdrawn and the current turned on by closing the switch *S*. If now the end of the core *C* be introduced into the coil, it will be found that it is strongly pulled inwards, and this pull increases as more of the core enters the coil, reaches a maximum, and then decreases until the core, if longer than the coil, lies symmetrically within it, with equal lengths sticking out at each end. If the core is withdrawn a few inches from this position and released, it will, provided the interior of the solenoid is smooth, oscillate about the central position, and finally settle down in that position, as if it were constrained to do so by elastic bands. The experiment is a very striking one.

The key to the movements of the soft-iron core in this case, as well as the movements of all kinds of soft-iron armatures, will be found by remembering the following principle, which can be demonstrated experimentally, and also deduced from the principles of magnetic induction already enunciated:—Whenever part of a magnetic circuit consists of soft iron free to move, the *soft iron will move* in such a direction as *to diminish the magnetic reluctance of the circuit.* In the experiments just described the magnetic circuit of the field of the solenoid has manifestly the least reluctance when the core is in the central position; hence if the core be free to take up that position, it will do so.

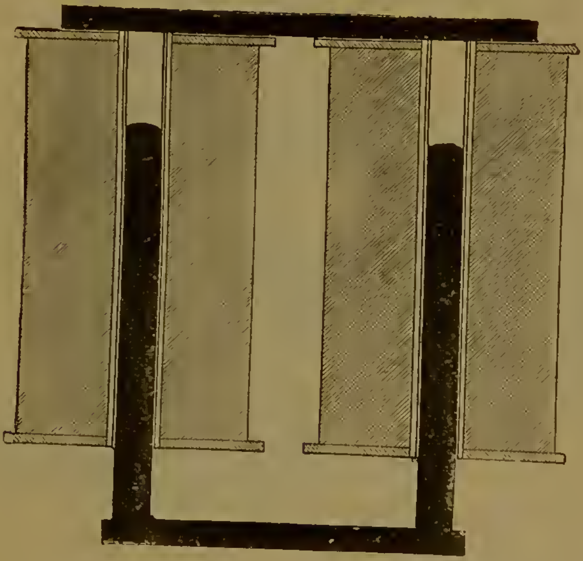

Fig. 87.—Electro-magnet of Brush Arc Lamp.

The coil-and-plunger principle is practically applied in many electro-magnetic mechanisms, and especially in arc lamps. One of the best known forms of these is the Brush Arc Lamp, the regulating magnet of which is shown in section in Fig. 87. It is a double-coil electro-magnet, and the deep black parts represent the iron of the magnetic circuit. The cores are movable, and are connected by a cross-piece, and when the current is turned on they are drawn in towards the yoke seen at the top. In this way it is obvious that the reluctance of the circuit is diminished in accordance with the general principle just enunciated.

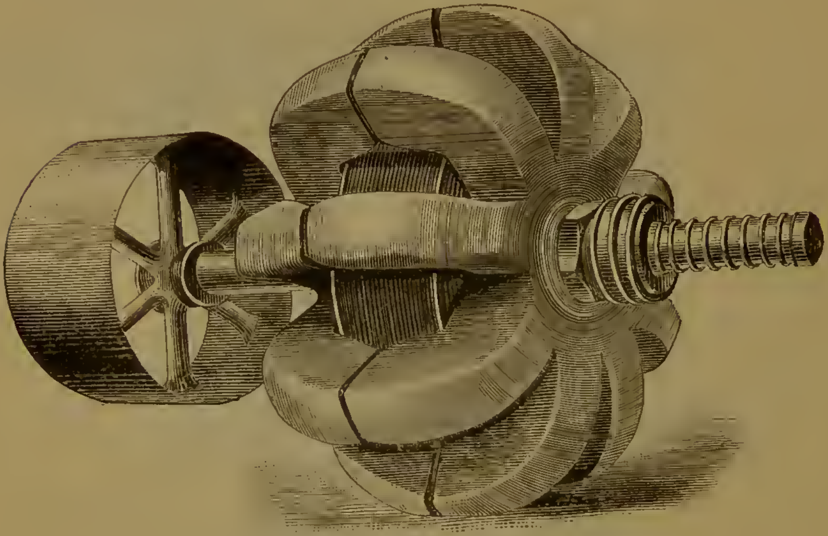

Fig. 88.—Field-Magnet of a Mordey Alternator.

As a final illustration of the strange forms that electro-magnets may assume, we show in Fig. 88 the field-magnet of the first Mordey Alternate Current Dynamo. The magnetising coil can be seen encircling the central shaft, and from this shaft on both sides of the coil there spring out the curious polar projections which curve round and almost enclose the coil. The polar projections coming from the two sides do not quite meet: between them there is a narrow air-gap, and the special object of the design is to produce a very intense field in this narrow gap.

Magneto-Electric Induction.

Oersted's discovery (in 1819) of the action of an electric current upon a magnetic needle placed in its neighbourhood showed that a connection existed between electricity and magnetism. It led the way to all the facts of electromagnetism, with which we have just been dealing, and showed how it was possible to obtain magnetism from electricity, or, more strictly speaking, from the electric current. The converse problem of how to obtain electricity, either in the form of the electric current or otherwise, from magnetism, immediately became a most interesting and enticing subject, and was attacked by many experimenters. The problem, however, remained unsolved until the autumn of 1831, when Faraday obtained the first clue to its correct solution, and in the course of a few months, by a series of patient and brilliant experiments, laid bare the fundamental principles underlying the full solution, and gave to the world one of the most important discoveries of the nineteenth century. It has sometimes been said that Faraday's discovery was accidental, but, as a matter of fact, nothing is accidental to such a worker. It is true that he was not expecting the particular effect which gave him his first clue, but that effect was so slight that a less careful observer would have passed it over altogether. In the eleven years that had intervened since Oersted's discovery, it is quite possible that this effect had been produced more than once, but nobody had observed it, or if they had done so, they had altogether failed to grasp its significance. But even with the clue in his hand, Faraday had a great task before him, and it is impossible to admire too highly the ingenious manner in which, guided by a kind of scientific intuition, he hunted down the truth and placed the results of numerous experiments upon a firm and simple basis of well-ascertained fact.

What, then, was the observation which, when diligently followed up, led Faraday to his great discovery? It was merely the momentary jerk of the needle of a galvanometer[1] at a time when, according to what was then known, it should have remained stationary. The first clue is thus described by Faraday[2]:—

> "Two hundred and three feet of copper wire in one length were coiled round a large block of wood; another two hundred and three feet of similar wire were interposed as a spiral between the turns of the first coil, and metallic contact everywhere prevented by twine. One of these helices was connected with a galvanometer, and the other with a battery of one hundred pairs of plates four inches square, with double coppers, and well charged. When the contact was made, there was a sudden and *very slight*[3] effect at the galvanometer, and there was also a similar slight effect when the contact with the battery was broken."

For our present purpose we shall find it more instructive to consider a later experiment published at the same time, and forming the first of the series in which the "Evolution of Electricity from Magnetism" is revealed.

A ring of soft bar-iron about six inches in diameter was overwound with two coils of copper wire, one of which was placed as before in circuit with a galvanometer, and the other with a battery and key by which the battery circuit could be made and broken. The arrangement is shown in Fig. 89, in which the ring *C* and its coils *A* and *B* are copied from the figure given in the *Experimental Researches*. On closing the battery circuit at the key *K*, "the galvanometer was immediately affected, and to a degree far beyond what has been described when, with a battery of tenfold power, helices *without iron* were used; but though the contact was continued, the effect was not permanent." "Upon breaking the contact with the battery, the needle was again powerfully deflected, but in the contrary direction to that induced in the first instance."

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[1] Descriptions of galvanometers and an account of the principles underlying their working will be found in Part II., Chap. IX., p. 335.

[2] *Experimental Researches*, 10, page 3. November, 1831.

[3] The italics are ours.

Now, when the battery circuit was made, we know that the effect of the current in coil *A*, on its soft iron core, would be to *magnetise* it, and that most of the magnetic lines set up in the iron would pass through coil *B*, since the magnetic reluctance of the path through the iron in coil *B* would be much less than that of any of the alternative paths through the air. Thus a lot of magnetic lines were suddenly pushed through the coil *B*, and the result was a momentary current in the circuit of which that coil formed a part. That the momentary current was due to the introduction of the magnetic lines into the coil connected to the galvanometer, Faraday showed by dispensing with the battery and the coil *A*, and introducing a permanent magnet into the coil *B*. Similarly he showed that the reverse momentary current on breaking the battery circuit was due to the withdrawal of the magnetic lines.

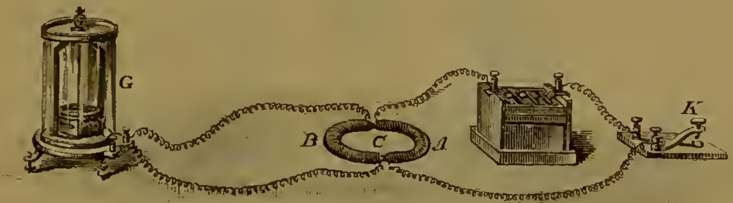

Fig. 89.—Faraday's Discovery of Magneto-Electric Induction.

We may remark in passing, that the fact that a current is induced in this experiment shows conclusively that the lines *actually pass through iron*, and do not simply begin and end on it when the iron is magnetised.

A convenient way of making experiments on magneto-electric induction is depicted in Fig. 90. *B* is a hollow bobbin or coil on which silk-covered copper wire is wound in exactly the same way as cotton is wound upon a reel. The inner and outer ends of the copper wire are connected respectively to the two binding screws. *G* is a galvanometer which is placed in simple circuit with the coil by means of connecting wires. No key or battery is used, and the galvanometer must be placed so far away that the movements of the magnet do not *directly* affect its magnetic needle. When a magnet *NS*, held in the hand, is moved towards the coil as shown, the needle of the galvanometer is momentarily deflected. When the motion ceases, the galvanometer needle comes to rest again in its original position; and if then the magnet be withdrawn, the needle is momentarily deflected in the opposite direction. The greatest effect in one direction is produced when the magnet is *introduced very rapidly* right *inside* the coil, and in the opposite direction when the magnet is *very rapidly withdrawn* from the coil. The directions of the movement of the needle are also reversed if the magnet is turned

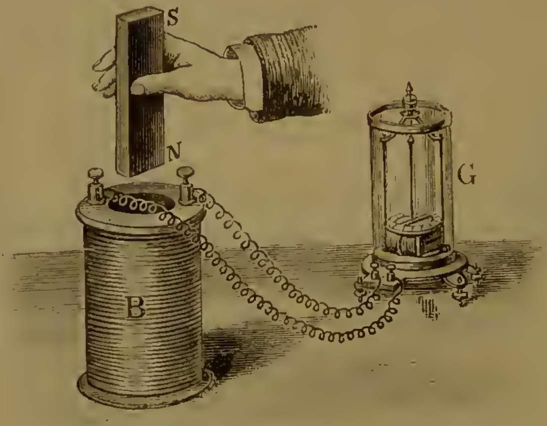

Fig. 90.—Induction of Electric Currents by the Motion of a Magnet.

round and brought up with its south pole nearest the coil, instead of its north pole, as in the figure. By bringing up the magnet in different ways, such as horizontally and otherwise, it will soon be found that there is no motion of the needle except when magnetic lines are introduced into, or withdrawn from, the space enclosed by the coil.[1]

We would remind the reader that the whole of the space round a magnet is in a state of strain, and that the magnetic lines to which we are referring are only meant to call up a mental and graphic picture of the directions and magnitudes of the strains. These magnetic strains and the lines depicting them are as much part of the magnet as its poles. They may be modified by the presence of iron, and by other actions in the external space, but if the magnet be moved they accompany it. Thus, in Fig. 91, if the magnet *S N* be moved nearer to the ring *R*, a glance at the direction of the lines will show that more lines will pass through the ring, and if the magnet be slipped right

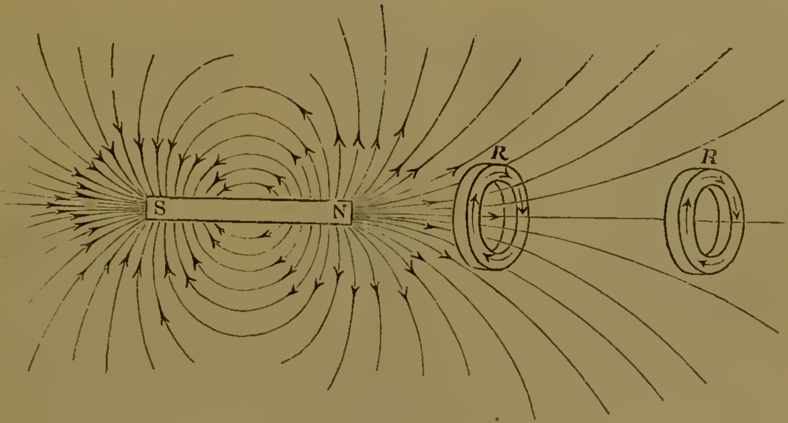

Fig. 91. Lines of Force and Conducting Ring.

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[1] Strictly speaking, this will only be the case when the connecting wires to the galvanometer are closely twisted together so that no magnetic lines can pass between them.

into the ring, all the lines which pass through the material of the magnet will pass through the ring. During the motion of the magnet towards and into the ring currents will be induced in the ring. Now, as regards the introduction of the lines, it is obviously immaterial whether we move the magnet towards the ring or the ring towards the magnet, and experiment shows that in either case the induced currents are the same, provided the rate of approach be the same.

The direction in which the induced currents circulate in the ring or in the coil in the various possible cases is very important. It is easily deduced for any given change of the enclosed lines by applying the following simple law first enunciated by Lenz, and known as **Lenz' Law**:—*The direction of the induced currents is such as to set up a field which will tend to* RETARD *the change that is causing the induction.*

To apply this law, we return to Fig. 90. If the N pole of the magnet is moved along the axis of the coil towards it, this motion would be retarded if the currents in the coil were such as to produce a virtual North pole at the top end of the coil, for that would *repel* the approaching N pole. Such a virtual North pole would be set up by currents circulating in the wires of the coil in a *counter-clockwise* direction as seen from the top end of the coil. The direction of the movement of the galvanometer needle shows that this *is* the direction of the momentary currents in the coil. Again, as the magnet is withdrawn, the N pole being downwards, its withdrawal would be retarded by the attraction of a South pole produced at the top end of the coil. The induced currents are found to be such as would produce such a South pole: they flow in a *clockwise* direction round the axis of the coil, and hence deflect the galvanometer needle the opposite way.

The direction of the circulation of the currents required to produce the various attractions and repulsions can be remembered by the "corkscrew" rule already given (page 149). This suggests another way of applying Lenz' law. If the motion of the magnet is such as to *increase* the number of lines of force passing through the coil or circuit, the induced currents will tend to pack lines through in the opposite direction, and thus *retard the increase.* On the other hand, if the motion of the magnet is such as to *decrease* the number of lines of force enclosed by the coil or circuit, the induced currents will tend to pack lines through in the same direction, and thus *retard the decrease.* It must, of course, be remembered that the lines of force of a magnet are regarded as running *from* the N pole to the S pole.

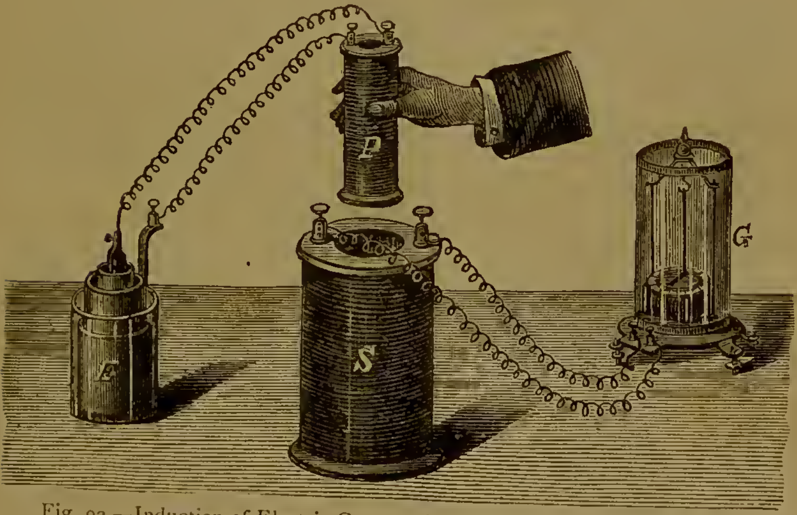

Fig. 92.—Induction of Electric Currents by the Motion of a Coiled Current.

In Fig. 91 we have indicated by arrows on the ring R the directions of the currents induced in it as the magnet is moved up. The reader may apply both the above methods to examine and check this result.

In the preceding we have for clearness always spoken of a *permanent* magnet being used in the experiments, but it is obvious that the same results would follow if an electromagnet or even a simple solenoid carrying a current were used. Thus the permanent magnet of Fig. 90 may be replaced by a coil, *P*, carrying a current as in Fig. 92. As this coil is moved up it will induce a momentary current in S in one direction, and as it is moved away there will be a momentary current in the opposite direction. A little consideration will show that in the first case, when the coil *approaches*, the *induced current* will be in a *contrary direction* to its own current; for the induced current must be such that the two nearest ends of the coils must have the same virtual polarity, and, therefore, when both are looked at from above, the two currents must circulate in opposite directions. Similarly, as the current coil *P* is withdrawn, a current must be induced in the coil *S*, which circulates round its axis in the same direction as that of the current in the receding coil.

We have above spoken of the lines as being introduced into the "coil or circuit"; the latter word opens up a wider aspect of the question. First, for the currents to flow at all there must be a *closed circuit*. Secondly, the currents which are induced in such a circuit depend on the change in the number of lines of force enclosed by the circuit *as a whole*. Thus, if in one part of the circuit the lines are being diminished or packed through in the opposite way at the same rate at which they are being introduced at another part of the circuit, no current will be induced. In Fig. 90 if the magnet be brought up *horizontally* to the centre of the outside of the vertical coil, no current will be observed; for one half of the coil has lines passed through it in one direction and the other half of the coil has an equal number passed through it in the opposite direction.

Again, there may be no movement of the galvanometer if the needle receives two opposite impulses very rapidly after one another. Thus, if the coil *B* in Fig. 90 be held over the floor and the magnet dropped right through, the tendency of the needle to move in one direction during the approach of the magnet is immediately followed by an equal but opposite tendency during the retreat. If very sensitive, the galvanometer needle may give a slight quiver, but there will be no large deflection.

There is another way of regarding the phenomena, which we shall find very convenient when considering dynamo machines. Whenever a current flows in a circuit, it is because an electromotive force has been somehow set up in one or more parts of the circuit. In the case of batteries, we have given reasons for supposing that E.M.F.'s exist at the metal-acid junctions. Now when momentary currents are induced in closed circuits by the motion of magnets, E.M.F.'s must be momentarily present in the circuit. Suppose, for instance, that a *very small* gap is made somewhere in the circuit, so that no currents can actually flow, but everything else remains as before. If now a magnet is moved as before near the circuit, we should expect to find that the *tendency* for the current to flow is set up in the conductors—in other words, that an E.M.F. is generated by the motion of the magnet. Experiment shows that this is the case, for we can detect and measure this E.M.F. with suitable instruments.

Where, then, are we to look for the "seat of the E.M.F.," or in what part of the conductor is it developed? We have seen that when the circuit is closed the current, and therefore the E.M.F., depends upon the rate of increase (or decrease) of the lines enclosed by the circuit. Now the lines of force are *closed curves*, and can, therefore, only get inside the closed circuit by passing across or cutting through the conductor. Suppose that, instead of thus entering at many parts of the circuit, they enter across a comparatively short length of it as in Fig. 93, in which the bar *A B* is supposed to be sliding along the rails $C\ D$ and $F\ H$, and is thus increasing the number of lines in the galvanometer circuit by the actual enlargement of the circuit. The change that is taking place is due to the movement of the slider, and it is not unreasonable to suppose that the E.M.F. that is driving the induced currents round the circuit should be situated in the slider. But the slider is merely cutting lines of force. Hence we are led to the principle that *whenever a conductor cuts lines of force, an E.M.F. is set up in the conductor at the place where the lines of force cut across it.* The direction of this E.M.F. depends upon the positive direction of the lines and the direction of motion; it can be deduced from the rules already given by supposing the conductor connected by sliding contacts, as in Fig. 93, with fixed conductors so as to form with them a closed circuit. Thus, if the vertical arrows represent the lines of force and the slider move from left to right, the induced current will be counter-clockwise in the circuit shown, and therefore the far end of the slider will be at a higher potential than the near end. The slider cutting the lines of force acts as an electrical pump, and behaves just as a battery would if it were placed in $A\ B$.

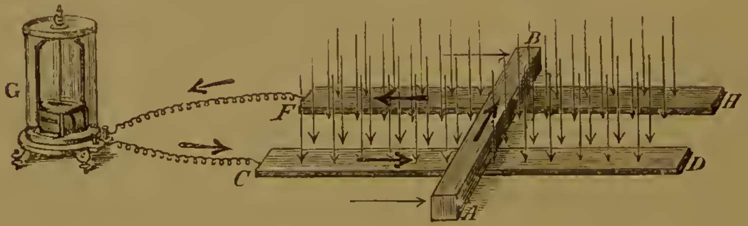

Fig. 93.—E.M.F. in Conductor cutting Lines of Force.

As an example, suppose a railway train travelling northwards at the rate of sixty miles an hour. The axles of the wheels are conductors cutting the earth's lines of force at a definite rate, and a calculable E.M.F. is set up in each of these axles. Unfortunately it is too small to be of any practical use.

Current Induction.—Another phase of the same class of phenomena was discovered and investigated by Faraday at the same time. It is frequently treated separately under the name of "current" induction, but the principles involved are the same as those we have just considered.

As already frequently pointed out, there is in the neighbourhood of an electric conductor carrying a current a field of magnetic force, and we have described the kind of field for various typical cases. Now this field is only present whilst the current is actually flowing. If, therefore, we suddenly *start* a current in a circuit, one effect is to set up this magnetic field, which increases in strength as the current grows until the latter has attained its full value. The magnetic lines may be pictured as spreading outwards from the conducting circuit as the current grows, and will, of course, eventually pass through any other closed conducting circuit which happens to be placed so as to lie across their paths. Now, according to the principles already enunciated, this packing of magnetic lines into the second circuit will induce a momentary current in it in such a direction as will tend to retard the putting in of the lines. We should, therefore, expect that the starting of a current in any circuit will cause a momentary current in any other closed circuit in its neighbourhood. This was, in fact, what Faraday observed in his first experiment described on page 170.

For example, if a make-and-break key be inserted in the battery circuit in Fig. 92, as shown in Fig. 94, then we should expect that whenever the key *K* is closed or opened there will be a momentary jerk of the needle of the galvanometer as long as the two coils are in the positions indicated. For when the coil *P* has no current in it, there is no magnetic field surrounding it, and no lines of force from it pass through the coil *S*. But when *P* bears a current, some of the lines of force due to this current will pass through *S*. The closing of the battery circuit is, therefore, equivalent to the bringing up of a magnet to the position of *P* from an infinite distance; and the breaking of the battery circuit is equivalent to the sudden removal of this magnet. In each case, therefore, currents will be induced in *S*; in the first case in such a direction as will tend to repel the coil *P*, and in the second case in such a direction as will tend to attract *P*. The first of these currents, *i.e.*, the current at *make*, it will be found must circulate round the common axis of the two coils in the *opposite* direction to the current in *P*; whilst the current at *break* will circulate round in the *same* direction as the current in *P*. These are sometimes referred to as *inverse* and *direct* currents, and the result is briefly stated thus :—On *making* a current *inverse* currents, and on *breaking* the current *direct* currents are induced in neighbouring circuits.

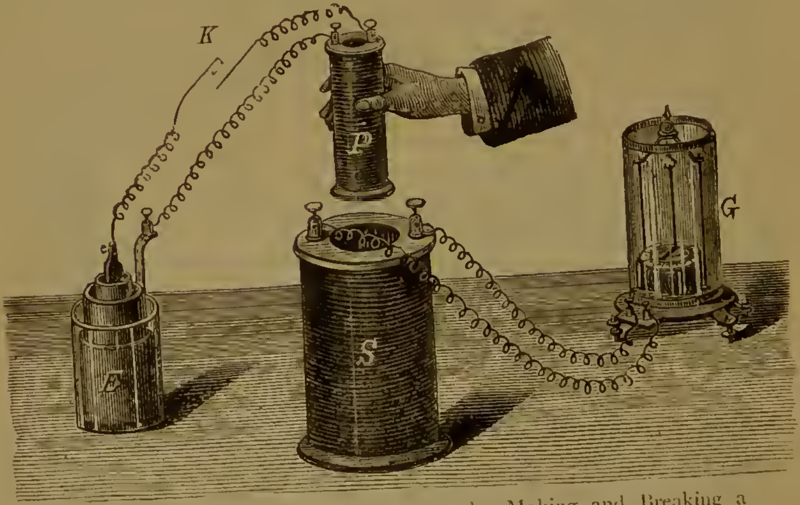

Fig. 94.- Induction of Electric Currents by Making and Breaking a Neighbouring Current.

The effect is even perceptible when the neighbouring parts of the two circuits consist of two parallel wires only, as in Fig. 95. On pressing the key *K* so as to start a current in *A B*, a momentary current in the opposite direction, as shown by the arrow, is induced in *D C*. The application of the preceding rules to this case is very easy. A current from *A* to *B* will cause lines to pass upwards through the circuit *D C H N* from below the table. Whilst these lines are being forced into the circuit, a current must be induced which will tend to force lines downwards from above to below the table. The direction of the current must, therefore, be clockwise in the circuit *D C H N*, that is it must pass from *D* to *C*.

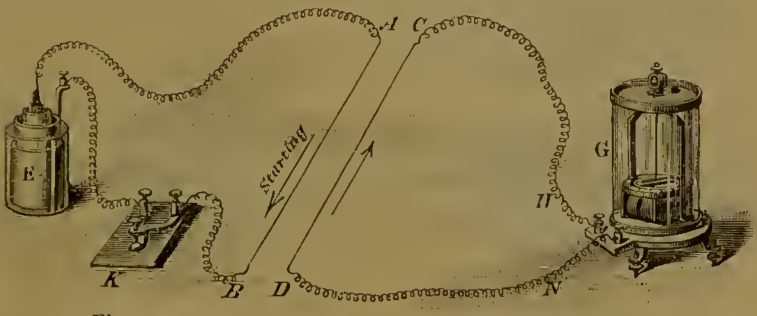

Fig. 95.—Induction between two Parallel Conductors.

Similarly, on breaking the battery current at the key *K* a momentary current will be induced in the wire *C D* from *C* to *D*. Also any *increase or decrease* of the current in *A B* will cause induced currents to flow in the circuit *D C H N during the time that the increase or decrease is taking place.* These induced currents in and from neighbouring circuits become of great importance in telephone work.

Induced currents may themselves give rise to further induced currents, and these yet again to others, and so on. The existence of these induced currents of the second and higher orders, as they are called, was very carefully investigated by Professor Henry, of Princeton, with the ribbon coils shown at the foot of the electro-magnet in Fig. 78. The principle of the phenomena is illustrated in Fig. 96. The coil I. is placed in circuit with a battery and key (not shown in the figure), so that a current can be passed through it and broken at pleasure. Coil II. is placed close to I. and in its magnetic field, and coil III. is in circuit with II. but at a distance from it. Coil IV. is similarly placed within the field of III., and its wire ends in two metallic handles which can be grasped by the observer. The making and breaking of the current in I. causes momentary alternate currents in II. and III., and the rise and fall of these currents give rise to still more complex currents in IV., the variations of which are physiologically perceptible to the observer as a nervous shock.

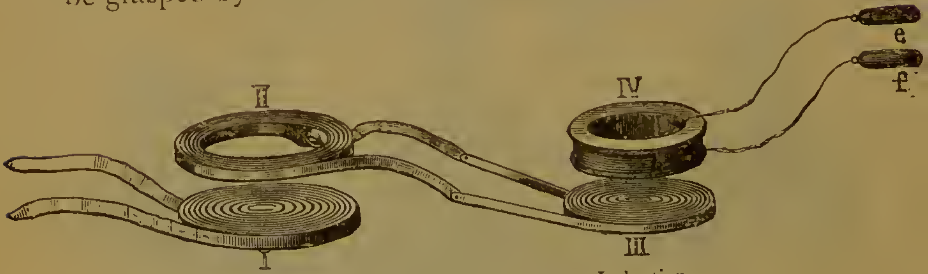

Fig. 96.—Higher Orders of Current Induction.

Self-Induction.—But the fact, that *the packing of lines of magnetic force into a closed circuit induces an E.M.F. in that circuit*, has a still further consequence. We have seen that when a current flows in any circuit, all the lines of force due to the current pass through the circuit. Therefore, *whilst the current is growing* in the circuit *the number of lines passing through it is increasing*. Thus, during this time, there must be an induced E.M.F. in the circuit, and a moment's consideration will show that the induced E.M.F. must act as a *back pressure*, and, therefore, *retard the rise of the current*.

This induced E.M.F. being due to the current's own lines of force is known as the E.M.F. of *self-induction.*

On the other hand, *when the circuit is broken*, the lines of force due to the current are taken out, and therefore an E.M.F. is induced in the circuit in the same direction as the E.M.F. of the electric generator, and tending to *retard the fall of the current.* In consequence of this added E.M.F. of induction the potential difference (P.D.) at the two sides of the break may rise so high as to cause a vivid spark. The effect is especially noticeable if the lines of force through the circuit, or the *inductance* of the circuit, are very great, as when an electro-magnet is included in the circuit. Thus, if a small battery with an E.M.F. of a few volts only be used to excite a large electro-magnet, the spark on breaking the circuit may be so long and vivid as to indicate a P.D. of hundreds of volts at the point where the circuit is broken.

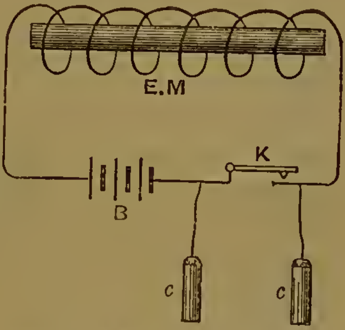

Fig. 97.—Effect of Self-Induction.

The rise of the P.D. at the two sides of the break may be made perceptible physiologically by a very simple experiment. Let the current from a battery B be sent through an electro-magnet E.M., and let a make-and-break key K be inserted in the circuit. Join two metallic handles *c c* by conducting wires to two parts of the circuit close to the key, but one on each side of it. If a person takes hold of the two handles with his hands, then when the key K is pressed he does not perceive anything, but when the key is raised so as to break the circuit, he will experience a sharp shock, though he could handle the terminals of the battery B without experiencing any sensation.

Another very instructive way of regarding the matter is the following. The space included in the magnetic field of a current is in a state of strain, and bodies in a state of strain have energy stored up in them which will do work as the strain is relieved. A familiar example is a coiled watch-spring, which, as it uncoils, drives the watch. But in order to store up this *strain-energy* in the body, or in the ether of the space surrounding the current, work must be done by some source of energy. Thus, whilst the current is growing in a circuit, the current generator is called upon to supply magnetic strain-energy to the surrounding medium, and therefore there is not so much of its energy available for driving the current, and the growth of the current is retarded. But when the circuit is broken, most of this stored energy is thrown back into the circuit, large electric pressures, or E.M.F.'s, are developed therein, and the bulk of the energy, unless some other work be provided for it, is expended in the heat, light, and sound of the spark. Part of it, however, is expended in extra heat in the wire.

In fact, in circuits of appreciable inductance the electric current behaves as if it had molar or mass inertia. A stream of water cannot be suddenly started or stopped in a pipe because of its mass, which necessitates an expenditure of energy to set it in motion, and this energy has to be taken out of it before it can be brought to rest. These operations take time. Similarly, an electric current, in the cases mentioned, takes time to get under weigh, and when attempted to be stopped, tends to go on. The difference between the two cases consists in the fact that the energy in the first case is stored in the water itself, whereas in the case of the current, the energy is stored in the surrounding ether.

This *quasi-inertia* of the current leads to many curious consequences, to which we shall frequently have to refer later.

We give one example of them here. An electro-magnet *S* (Fig. 98) is placed in circuit with a battery *B*, and a galvanometer *G* is placed as a by-path or *shunt* across the terminals of *S* at the points *a* and *b*. The battery current flows partly through *G* and partly through *S*, with directions indicated by the dark arrows, but the galvanometer needle is kept in its zero position by a pin against which it presses. On breaking the circuit at *K* the galvanometer needle is violently jerked away from the pin, showing the existence of a current, as indicated by the dotted arrows, in the opposite direction to the battery current. This is readily explained. The E.M.F. of self-induction brought into play on breaking the battery circuit is far greater in *S* than in *G*, because of the greater inductance of *S*. This E.M.F. is in the direction of the original current, but it now has a closed circuit through *S* and *G* in which to work; consequently it causes a rush of current (the so-called "extra-current") round this circuit, thus expending the magnetic strain-energy of the original current. The breaking spark at *K* will therefore be very small.

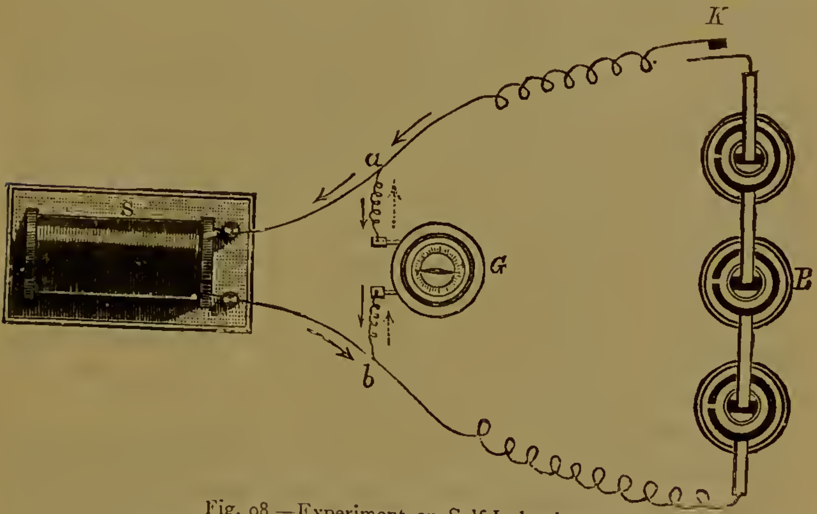

Fig. 98.—Experiment on Self-Induction.

Dynamo-Electric Machines.

INTRODUCTORY.

Although Faraday's discovery of magneto-electric induction was made in 1831, and shortly afterwards published to the world in language so clear that those who ran might read and understand, it was nearly fifty years before the rich harvest of fruit that can be directly traced to that discovery began to be gathered in. It must not be supposed that the discovery during that long interval was entirely unproductive, but the development was extremely slow, and mostly showed itself in the elaboration of laboratory apparatus and pretty experiments for the lecture table. But at last the time came when, with the improvement of the Dynamo Machine, engineers began to perceive that a new power for bending inanimate nature to their will had been put into their hands, and Electrical Engineering was recognised as worthy of study by those who direct our great manufacturing industries.

What, then, is a Dynamo-Electric Machine, or more shortly, a Dynamo, and how is it that its development has had and is still having so great an effect on the industries of the world? The first question may be answered formally thus :—*A Dynamo-Electric Machine is a Machine for converting mechanical energy into the energy of electric currents by moving conductors (usually of copper) which form parts of closed circuits, in a magnetic field, or by varying a magnetic field in the presence of such conductors.* The answer to the second question propounded above is also indicated in this definition, for wherever mechanical energy has to be transmitted from a distant source to some other place where it is desired to utilise it, the electric current forms a very convenient means of effecting the transmission; and, as we shall see in the sequel, the energy of the current can at the desired point be reconverted into the mechanical or any of the other forms of energy best suited for the particular purpose in view.

Before we proceed to consider the details of the appliances used in this method of transforming mechanical into electrical energy, it would be well to emphasise the fact, that in all methods of generating electric currents by means of magneto-electric induction mechanical energy *is* used up. The method, as we have explained in the previous pages, essentially depends upon the variation of the number of lines of magnetic force passing through a closed conducting circuit. This variation may be caused by moving a magnet towards or away from the circuit, and it is perhaps not easy to see at first whence the energy of the induced current in the circuit is derived. It is found, however, as a matter of experiment, that to move a magnet towards a *closed* copper ring, as in Fig. 91, requires a greater force than if the ring be cut across somewhere so that it does not form a closed circuit and currents are unable to flow in it. The additional energy thus used up is converted into the energy of the induced electric current, which in this case is expended in warming the ring. But the variation of the number of lines passing through it may be caused by moving the ring itself, and here again it is found by experiment that to move the closed ring towards the magnet requires the expenditure of more energy than if the ring be moved through exactly the same space when the magnet is not present. Once more the additional energy is converted into the energy of the induced current, which is eventually expended in heating the ring.

In these cases, however, the amount of energy transformed, first into current energy, and then into heat energy in the ring, is extremely small, and the additional resistance to motion, as well as the small amount of heat produced, might both escape notice. But by increasing the intensity of the field and the rapidity of the motion, both of these may be made very sensible. In Fig. 99 is shown a piece of apparatus constructed long ago by Foucault for this purpose. On the right is placed a large electro-magnet *E*, whose pole-pieces, *N* and *S*, consist of large rectangular

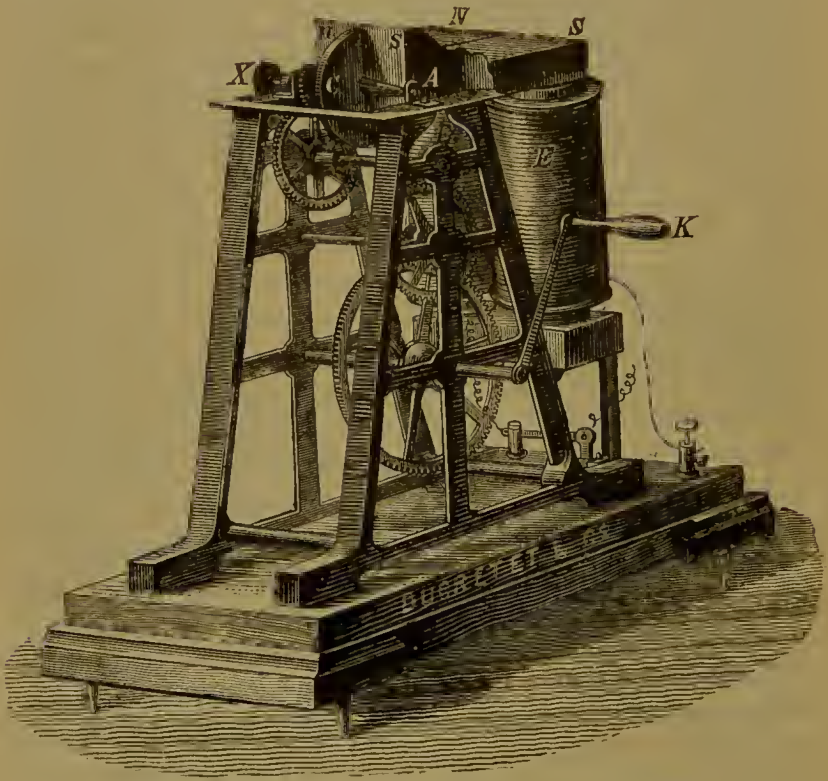

Fig. 99.—Mechanical Energy Absorbed by Induced Currents.

blocks of iron so placed relatively to one another that only a narrow gap of air separates them. When the electro-magnet is excited by a strong current, a very intense field of magnetic force is produced in the space between the pole-pieces. Into this narrow gap the disc *C* projects to nearly its full radial depth, but does not touch either of the iron poles. The axle *A X*, upon which the disc *C* is fixed, is connected by the toothed-wheel gearing with the handle *K* in such a manner that when *K* is turned slowly *C* revolves rapidly. If now the electro-magnet is unexcited and the handle *K* turned, no more resistance to motion has to be overcome than that caused by the mechanical friction of the gearing. Let the handle be so turned until the speed of *C* is fairly great, and then let *E* be excited by passing a current through its coils. The experimenter turning the handle immediately feels an enormous increase of the mechanical resistance to motion, and if he is able to keep up the speed at all, he finds that he has to do much more work than previously. It is as if the disc *C* were suddenly plunged into a viscous resisting medium, such as treacle or coal-tar, although to the eye the space between *N* and *S* does not appear to be altered. Should the speed be kept up for a minute or two, it will be found that the disc *C* becomes hot. How is this ? It is because the disc *C*, consisting of a fair expanse of sheet copper, offers the choice of an infinite number of closed conducting circuits to any currents which may tend to flow. As each of these circuits enters the magnetic field it has a current generated in it in one direction, and another in the opposite direction as it leaves it. But according to the general law already enunciated (page 174) these currents set up magnetic fields of such a nature as to oppose the change that is taking place, just as the motion of the North pole of a bar magnet towards the North pole of another bar magnet is opposed by the magnetic repulsions. Consequently more energy has to be used to spin the disc in the magnetic field than when the field is not present : this energy is directly converted into the energy of the electric currents generated in the disc, and in its turn is spent in heating the material of the disc. The existence of these currents in masses of solid conducting material moving through a magnetic field, or placed in a varying magnetic field, was first pointed out by Foucault, and they are usually called either *Foucault currents*, or *parasitic currents*, or *eddy currents*. They play an important part in the design of dynamo machinery.

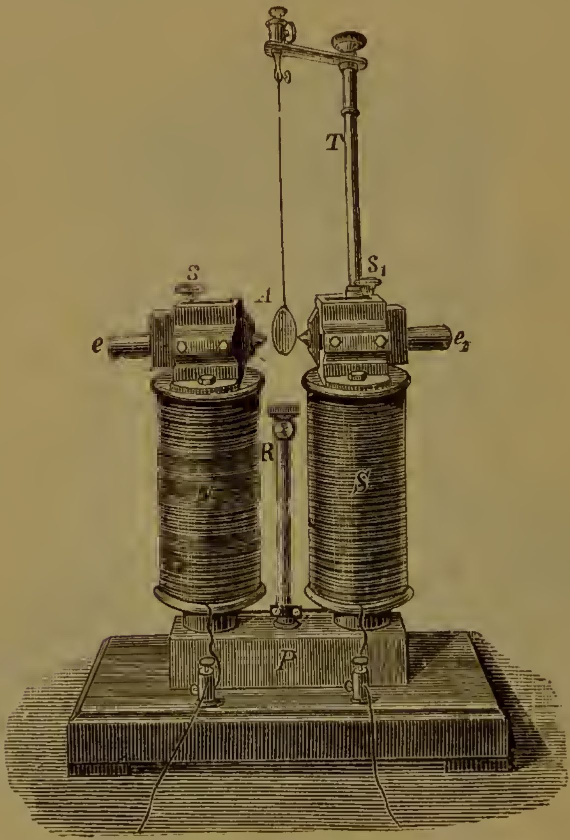

Fig. 100.—Disc spinning in Magnetic Field.

A still simpler experiment devised by Faraday may be performed by anyone who possesses a good electro-magnet. Suspend a disc (in Faraday's original experiment a cube) *A* of copper or silver between the poles *S S* (Fig. 100) of the electro-magnet by a thread of silk twist. If the disc be allowed to hang freely and the magnet be unexcited, the silk begins to untwist until the disc is spinning at a rapid rate. Now let the current be sent through the coils, and immediately the motion of the disc is arrested, and it becomes almost stationary, turning only very slowly and apparently with great difficulty, in the seemingly unaltered space. The stoppage of the rapid motion is due to the currents developed in the disc setting up magnetic fields which oppose the motion. The magnitude of these currents depends, as we know, upon the rapidity of the motion, which, therefore, has to slow down to such a point that the opposing magnetic forces called into play are comparable with the very feeble untwisting force of the silk.

The experiment may be varied by mounting a plate or a ring of copper, so as to swing like the bob of a pendulum, between the poles, when similar results will be obtained.

These simple experiments will, we hope, show the reader that the production of magneto-electric currents requires the expenditure of mechanical energy. We have purposely chosen illustrations in which the closed electric currents are small and compact; but since the resistance to motion is due to the magnetic field set up by the currents induced in these moving circuits, the mere size of the circuits will only influence the magnitude of the effect. Moreover, a moving part of the circuit may be connected by sliding contacts with a fixed part, so that a path is provided for the induced current, and then if the first part of the circuit be moved in a magnetic field, the same resistance to motion due to the same causes will be developed. In what follows, we wish the reader to bear these considerations in mind, though to avoid wearisome repetition we may not always specifically direct his attention to them.

Returning to our definition (page 106) we observe that a dynamo machine must be so constructed that either a closed circuit or part of a closed circuit can be moved in a magnetic field, or that the magnetic field passing through some part of a closed circuit can be varied. From the fundamental principle of magneto-electric induction, we also know that increasing the number of lines of force passing through a closed circuit gives a current in one direction, and decreasing them gives a current in the opposite direction. Now a closed circuit is necessarily of finite dimensions, and there is also a limit to the magnetomotive force which the most powerful currents used to excite electro-magnets can give us, for obviously we cannot use such currents as would fuse the conductors carrying them. It is, therefore, plain that we cannot go on increasing indefinitely the number of lines of force through our closed circuit, but that we must eventually reach a point, depending upon the greatest intensity of the magnetic field we can produce and the size of our closed circuit, at which we can pack no more lines through the latter. But currents are only induced when the number of lines is *changing*. When, therefore, the circuit encloses the *maximum* number of lines, we can only fulfil the last condition by beginning to *diminish* the number of lines passing through it. But this will give us a current in the *opposite* direction to that obtained during the increase of the lines. Also the process of diminution must come to an end, to be followed again by one of increase, which will restore the current to its first direction, to be again reversed later on. Thus, as a primary condition of this method of generating a current, we see that the currents originally set up must be alternately in opposite directions; such currents are known as *alternate currents*.

As an illustration, consider the case of a rectangular loop of wire (Fig. 101[1]) mounted so as to rotate between the poles N S of a large magnet. When the loop is vertical, it embraces the greatest possible number of lines of force of the field; when it is horizontal, as shown by the dotted lines, it has no lines of force passing *through* it, for it must be remembered that by this term we mean that the lines of force actually thread through the *plane* of the circuit from one side to the other, and do not merely pass in through the material of the wire at one side and out through the material of the wire at the other, never leaving the plane of the loop.

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[1] For this and many of the figures illustrating the theory of the dynamo the author is indebted to the kindness of Dr. Silvanus P. Thompson.

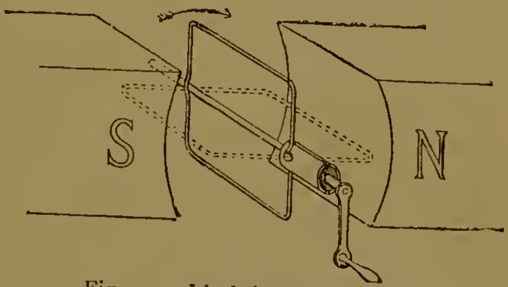

Fig. 101.—Ideal simple Dynamo.

Starting now from the vertical position as shown in the figure, let the loop be turned in a clockwise direction. The lines of force of the field run from the pole N to the pole S. Let us imagine ourselves looking at the loop from the N pole. As the loop rotates, the number of lines of force which were passing through it in the vertical position becomes less. Therefore, if the loop be a continuous closed one, currents will be set up in it which will tend to stop this change, *i.e.*, which will pack into it lines of force in the same direction as those which are being cut out. Thus, looking from the N pole, a *clockwise* current will be set up in the loop as it passes from the vertical to the horizontal position. In the same way it may be shown that as the loop passes from the horizontal to the vertical position in its continuous rotation, a counter-clockwise current will be set up in it *as seen from the N pole*. But we would now be looking at the other face of the wire, and, therefore, *in the wire* the direction of current is the same in this second quarter-revolution as in the first quarter, viz., from *front to back* along the wire which has been sweeping past the N pole. But a change occurs as we enter upon the third quarter-revolution. The lines, which have been getting threaded through the loop during the second quarter-revolution, have now reached a maximum, and they begin to be cut out again. Thus, there is a real reversal of current in the loop, whether we look at its direction from the N pole or think of its direction in the wire. It becomes *clockwise* as seen from the former, or from *back to front* in the wire which is beginning to sweep over the face of the S pole. Finally, in the fourth quarter-revolution the induced current retains the same direction from *back to front* in *this* wire as in the third quarter, though it again changes its direction as seen from the N pole.

To sum up: starting from the vertical position, there is an induced current in the loop from *front to back*, along the wire which starts at the top, during the whole of the first half-revolution; during the second half-revolution the current in the same wire is reversed.

We have spoken throughout of *currents* being set up in the loop, but if the loop be not quite continuous, that is, if there be a small non-conducting gap in it, say at the front end, no currents can flow; but the *tendency* for the currents to flow caused by the cutting of the lines of force will exist. In other words an *Electromotive force* will be set up in the loop in one direction during the first half of a revolution, and in the opposite direction during the second half. The magnitude of this E.M.F. depends, as we have seen, on the *rate* at which the lines of force are cut by the conductor. Now supposing the field uniform and the lines straight, in the vertical position the loop, for an instant, is not cutting lines at all; it is simply sliding along them. At this instant, therefore, the reduced E.M.F. is zero. As the loop swings round at a uniform speed it cuts the lines at a gradually increasing rate until it reaches the horizontal position, when, for an instant, it is moving at right angles to the lines and is cutting them at the greatest possible rate. At this instant the E.M.F. has its *maximum* value. It then falls off to zero when the loop is again vertical, reverses, rises to a negative maximum, and falls off again to zero as the revolution is completed.

This rise and fall of the E.M.F. is graphically depicted in Fig. 102, in which the different angular positions of the loop are plotted along the horizontal central line, and the E.M.F. induced in it is measured vertically *upwards* when it is in one direction in *the wire*, and *downwards* when it is in the opposite direction. The points so found are joined and form the curve. Thus the distance of any point on the curve from the central line represents on some scale the E.M.F. in volts in the loop at the instant it is passing the corresponding position as specified on the horizontal scale. Position 0° represents the vertical position of the loop, and the other positions are measured round as angles from this. Thus the first horizontal position is 90°, the next vertical position 180°, the next horizontal position 270°, and the complete revolution is denoted by 360°, when all the changes begin to repeat themselves in the same order.

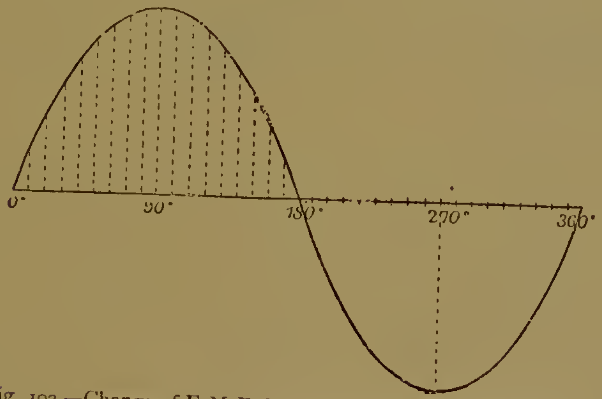

Fig. 102.—Change of E.M.F. in Loop Rotating in Uniform Field.

The particular scale of volts depends on the size of the loop, the strength of the field, and the angular speed, this latter being supposed uniform. It has, therefore, not been marked on the diagram, which is meant to represent the general case.

If there is a complete circuit, these various E.M.F.'s produce the corresponding currents. But the circuit need not be completed by the loop itself, which may be cut, and its ends joined to an outer conductor or series of conductors, which completes the circuit exactly in the same way as the wire joining the poles of a cell completes its circuit. The outer circuits, however, being fixed and the loop rotating, the connection between the two must be made by some kind of sliding contacts or *brushes* as they are usually called.

According to what we have just shown, *each* end of the cut loop on either side of the gap will be alternately positive and negative; or when the loop is in some parts of its revolution the current will tend to flow from one of these ends round the outer circuit, and when it is in other parts of its revolution the current will tend to flow from the other end. Thus, if a particular end of the outer circuit is always in contact with the *same* end of the wire loop, the currents in this outer circuit will be *alternate currents*, of the same kind as the currents that would circulate in the loop if it were closed on itself.

A method of making the connections so that such alternate currents may be set up in an outer fixed circuit is shown diagrammatically in Fig. 103. One end of the loop is joined to the metal cylinder or barrel *a*, the other is joined to the shorter metal ring or sleeve *A* which is slipped over the cylinder but is separated from it by a ring of insulating material such as vulcanised fibre. *B* and *b* are two fixed brushes or strips of copper under which the ring *A* and barrel *a* respectively slide. The ends of the outer circuit *C* are permanently connected to *B* and *b*.

Now sometimes *B* is positive and *b* negative, and at other times *b* is positive and B negative. The current in *C* is, therefore, sometimes in one direction and sometimes in the other, and there are thus alternate currents in *C*. Fig. 103 in fact shows the method of connection with the outer circuit in those alternate-current dynamos which have the coils under induction movable (*see* page 208).

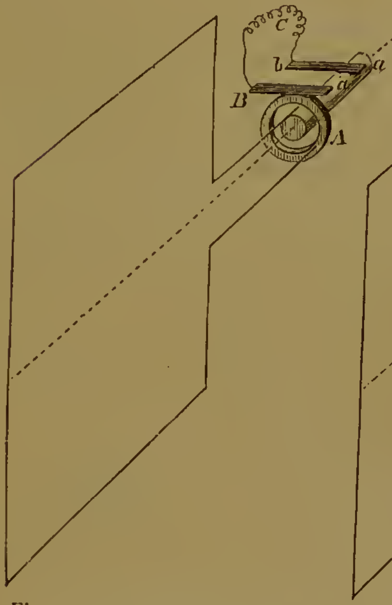

Fig. 103.—Connections of Loop for Alternate Currents.

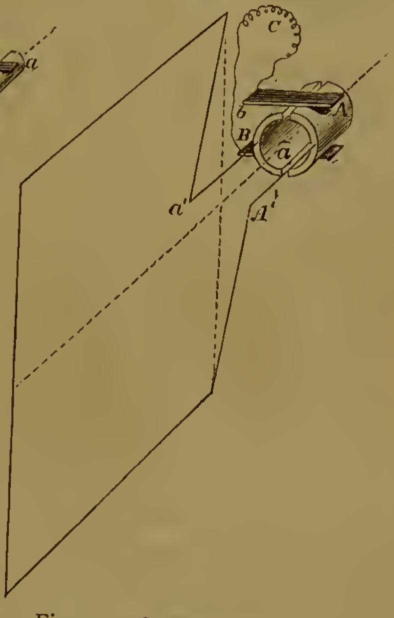

Fig. 104.—Connections of Loop for Continuous Currents.

If the current in the outer circuit is required to flow always in the same direction, a different method of connection is necessary. We must so arrange our contacts that at the moment when the two ends A′ and *a*′ (Fig. 104) of the loop are about to reverse their relative potentials, the connections with the ends of the outer circuit must be automatically reversed. This is done by using a two-part *commutator*, which will commute or change the connections at the right moment. The simplest form is the split-ring commutator shown diagrammatically in Fig. 104, and in section, with the sliding brushes, in Fig. 105. A short piece of brass or copper tube of convenient diameter is cut into two parts A and *a* parallel to its axis, and these two parts are separated a little way and fixed to an insulating hub *H* which turns on the axle *X* on which the loop is mounted. The ends *A′* and *a′* of the loop are joined to the two parts *A* and *a* of the split tube, and the fixed brushes *B* and *b* are so adjusted that they slide from one section of the tube to the other when the plane of the loop is vertical, that is just when the E.M.F. is changing sign. Thus the current in any outer circuit joined permanently to *B* and *b* is continuously in the same direction. But with a single loop such a current would be very unsteady, as it would fall to zero and rise to a maximum twice in each revolution of the loop.

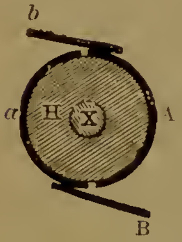

Fig. 105.–Two-part Commutator or Collector.

Another simple case is of importance. Instead of a loop rotating in the magnetic field let a ring of iron *I* (Fig. 106) be rotated, and on this ring let a few turns of a small coil be wound and its ends brought down to a two-part commutator on the axis of rotation. The position of the magnet-poles is the same as before, and may be seen in Fig. 101. The lines of force of the field will be drawn through the iron ring as they pass from pole to pole, but the general relation to them of the ring in its different positions will be much the same as in the loop. At the top the coil embraces a maximum number of the lines but is not cutting any; the E.M.F. in it is therefore zero. When at the right-hand

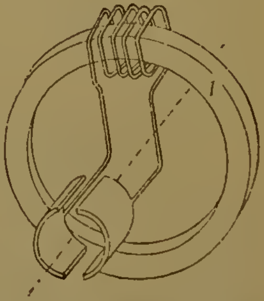

Fig. 106.—Simple Rotating Iron Ring and Coil.

end of the horizontal diameter no lines pass through the coil, but it is cutting them most rapidly, and the E.M.F. is a maximum. At the bottom the case is similar to the top, but the E.M.F. is about to change over the other way. From the bottom to the top the E.M.F. is reversed, and rises to a negative maximum when the coil is at the left-hand end of the horizontal diameter. If, therefore, the ends of this coil are joined to an outer circuit through the two-part commutator and sliding brushes as before, this circuit will receive a continuous but unsteady current.

These simple cases have been dealt with in great detail, because a clear understanding of them will enable our readers to grasp with little difficulty the more complicated cases of magneto-electric induction which occur in actual dynamos.

Leaving for a time the case of alternate currents, we shall now consider how the unsteady continuous currents of the simple loop and the one-coil ring may be made steadier. We should first explain, however, that the part of the machine in which currents are generated by induction is called the *armature*, a name which was originally applied to the keepers or pieces of soft iron joining the poles of horseshoe permanent magnets (page 158). As *relative* motion of the magnetic field and the armature coils is all that is needed to induce currents in the latter, the armature is not always the moving part of a dynamo. Sometimes, especially in alternate-current machines, the armature is stationary and the field-magnet is rotated. It is a matter to be decided by mechanical convenience.

There are several types of armatures for continuous-current machines, but those built on the model of the two simple cases just considered are most frequently met with. They are called *drum armatures* and *ring armatures* respectively. We take the latter first.

Ring Armatures.—Fig. 107 represents diagrammatically the connections of a Gramme-ring and its commutator.

The ring consists of a central core built up of iron wires varnished so that they are electrically insulated from one another. This core is then continuously overwound with insulated copper wire, which forms a single closed coil overlying the whole of the core. In Fig. 107 this copper conductor is for clearness represented as separated into eight distinct coils, but it should be noticed that these coils are so joined together as to form one continuous closed circuit, all the spirals of which pass in the same way round the ring. The eight junctions of the separate coils are connected by copper wires to the eight conducting strips of the eight-part split tube commutator, which for the present may be regarded as the two-part commutator already described still further divided, and mounted as before on an insulating hub. The brushes are also shown in the figure.

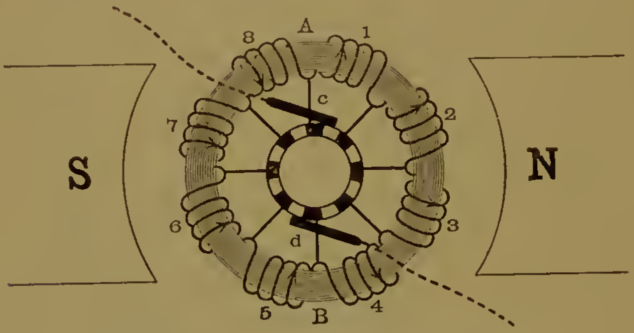

Fig. 107.—Simple Gramme Ring and Commutator.

For simplicity suppose the outer circuit to be a closed one, and that the induced E.M.F.'s give rise to the corresponding currents; also that the direction of rotation is clockwise. Coil No. 1 is passing from a position in which it encloses a maximum of the lines, and the lines through it are decreasing; as seen from N it will have a clockwise current induced in it, for such a current would tend to restore the departing lines according to the corkscrew rule. This current would flow from the inside to the outside of the ring on the near wires, and such a flow is indicated by the arrow-heads. No. 2 coil will be affected similarly, but the induced E.M.F.'s will be greater, as it is cutting lines more rapidly. No. 3 coil has passed the minimum position, and is enclosing more and more lines of force as it rotates. Seen from N the currents in it will be counter-clockwise, but in the near wires this still means a current which is radially from inside to outside. No. 4 coil behaves similarly, but with weaker E.M.F.'s. In coil No. 5, which is losing lines of force, the currents should be clockwise, as seen from N, and therefore radially from outside to inside on the near wires. Similarly examining coils 6, 7, and 8 separately, it will be found that the currents in them are all from outside to inside in the near wires. The result of all these actions is that all the currents on the right-hand side of the ring are flowing upwards towards the junction *c* and away from the junction *d*, and all those on the left-hand side are also flowing upwards towards *c* and away from *d*. From symmetry the E.M.F.'s on the two sides should be equal, and therefore, if no external path is provided for the currents, these E.M.F.'s will cancel one another, and no current will flow, although the wires of the ring form a closed circuit; but the point *c* will be at a higher potential than the point *d*. If now the junctions *c* and *d* be joined by a conducting circuit through the commutator segments, and the sliding brushes, the currents from both sides of the ring will combine to flow through this outer circuit, in which a continuous current will be maintained as long as the rotation of the ring is kept up. This current will also be much steadier than when only a single coil is used, for in every position of the ring there are coils on the right and left, in which considerable E.M.F.'s are being induced. As each coil passes across the positions of zero induction, or neutral positions, at A and B it is transferred from one side to the other of the ring at the moment its induced E.M.F. changes, thus the effect of its change upon the total available E.M.F. is partly smoothed out. Also the changes in the induced E.M.F.'s of the other coils, as a brush slides across one commutator segment, are not very great. Calculation shows that when the ring is divided into eight segments, as in the figure, the fluctuation is only

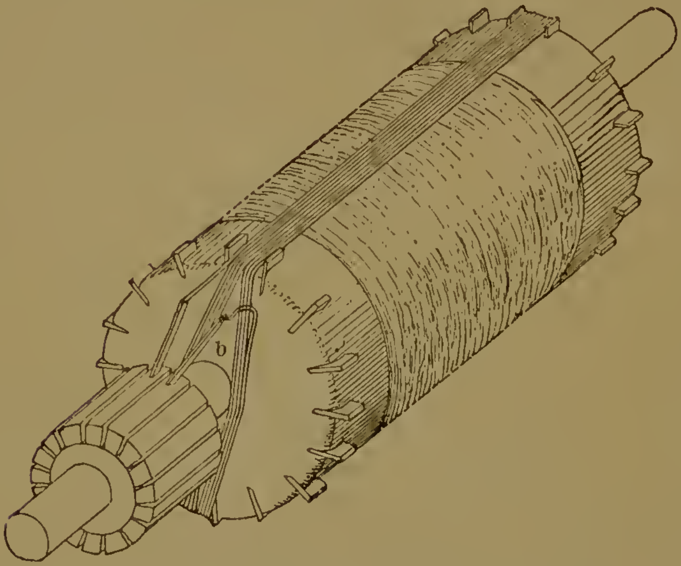

Fig. 108.—Method of Winding Siemens Drum Armatu e.

3·8 per cent. of the maximum value, and if the number of segments and of corresponding commutator bars be increased to 40, the fluctuation is only 0·14 per cent., or less than $1\frac{1}{2}$ parts in 1,000.

Drum Armatures.—The simple loop of Fig. 106 can also be built up into an armature which will give a steady continuous current by longitudinally winding an insulated wire in continuous loops upon a hollow drum or cylinder of iron. The method of doing this is partly shown in Fig. 108, which represents the Siemens Drum Armature partly wound. Only one coil, consisting of eight loops, is shown in position with its two ends joined to two consecutive bars of the 16-part commutator. The next coil might be wound in the space marked out by the next set of wedges at the extremities of the drum, one end being soldered to the radial bar *b* and the other to a bar connected with the next segment of the commutator. Then a third coil could be wound in the next space, and so on, until the whole sixteen coils were in position. There will then be two coils between each set of wedges. As a matter of fact, to lessen the danger of the breakdown of the insulation, the coils are wound on in a slightly different order, though otherwise the final result is the same. After the first coil is wound on, the armature is turned completely over, and what may be called No. 9 coil is wound on top of it, and eventually connected to its proper commutator segments. Then No. 2 coil is wound on and followed by No. 10 coil wound on top of it; and so on, till the whole sixteen coils are in position. Also the commutator is not slipped on to the axle until all the coils are wound. It is then put in its place and the necessary junctions made.

When such an armature is placed in the field between two magnet-poles, a sequence of inductions takes place similar to that we have described in detail when considering ring armatures. One half of the coils sends a current past one side of the commutator towards one brush, and the other half sends an equal current past the other side to the same brush; these currents unite to flow round the outer circuit to the other brush.

One inconvenience in the winding of drum armatures is the bunching up of the wires at the two ends of the drum where they overlay one another. Many ingenious devices have been patented for avoiding this difficulty.

Pole Armatures.—Instead of being wound with the planes of their coils perpendicular to the direction of motion, these planes may be parallel, as shown diagrammatically in Fig. 109. Such armatures are called *pole* armatures, but are not much used in continuous-current machines. When the radial poles of the armature are horizontal, the coils surrounding them enclose a maximum number of the lines of force, and the induced E.M.F. in them is zero. When the poles are vertical, no lines of force pass through the coils, but the rate of cutting, and therefore the E.M.F., is a maximum. Following out the reasoning applied to Fig. 107, it will be seen that the brushes should be placed at the ends of a horizontal diameter instead of the ends of a vertical one as in the two previous cases.

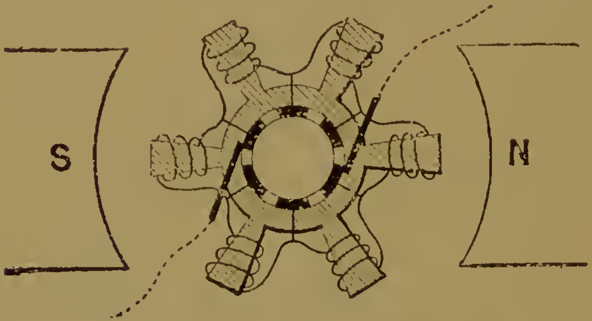

Fig. 109.—Simple Pole Armature showing Connections.

Disc Armatures.—These armatures are built upon a principle first employed by Faraday, who, in this particular experiment, was the inventor and constructor of the first dynamo machine. The special advantage of such an armature is that it gives a continuous current of electricity without the use of a commutator. The apparatus is similar to that (Fig. 99) used subsequently by Foucault to show the existence of "eddy currents." A copper disc is rotated (Fig. 110) between the poles *n s* of a magnet which, in some of Faraday's experiments was a permanent magnet, in others an electro-magnet. Collecting springs of copper or lead slide upon the circumference and the axis of the disc, as shown in the detached figure on the left. When the disc is rotated in a clockwise direction, radial currents flow in it from the axis towards the circumference, and in the outer circuit from the slider b_1 to the slider b_2. This action is in accordance with the rules already given, for as each vertical radius cuts across the poles, its motion will tend to increase the lines of force in the circuit of which it temporarily forms a part; hence the production of the above-named currents.

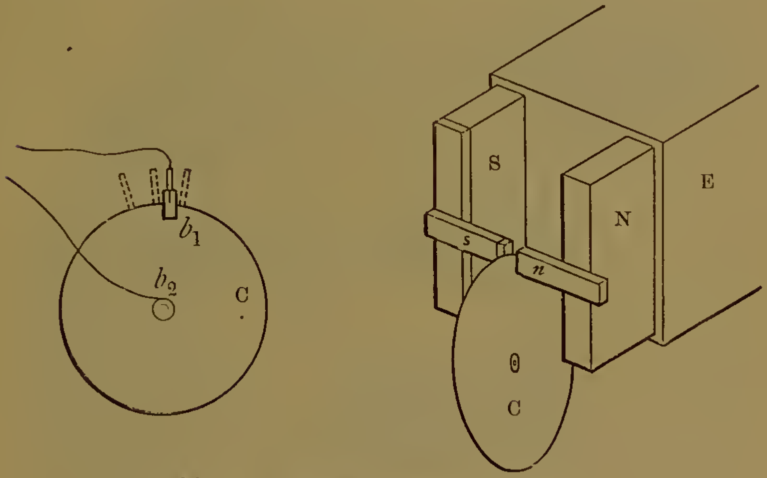

Fig. 110.– Faraday's Simple Disc Dynamo.

The construction of large machines of this type has not met with a great measure of success, as there are several serious practical difficulties in the way. The chief are the friction of the circumferential brush, and the production of wasteful "eddy currents" in the revolving disc even when slit radially.

The four classes of armatures just described are all adapted to give continuous or unidirectional currents in the attached external circuit. These armatures do not exhaust all the varieties that have been devised for the purpose, but they are sufficient to indicate the principles involved. In some forms the different coils are not joined in a continuous circuit, but have their ends brought to parts of specially constructed commutators, on which their currents are combined by properly placed brushes.

Alternate Current Armatures.—In another large class of machines no attempt is made to "commute" or "rectify" the alternate currents which we have seen (page 192) must always be induced in the armature coils. These currents are delivered into the outer circuit in the form in which they are generated, namely, as *alternate currents.* If the armature be fixed, it can be joined permanently to the outer circuit through appropriate switches; but if it be the moving part of the dynamo, the connection between it and the fixed external circuit must evidently be made by sliding contacts of some kind.

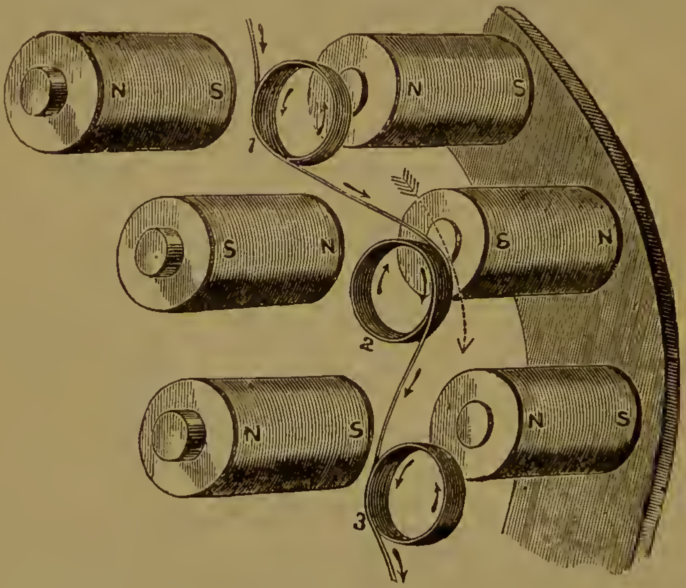

Fig. 111.—Successive Coils of an Alternate Current Armature.

Besides the absence of the commutator, there is another marked, but not theoretically essential, difference between continuous and alternate current dynamos, in the shape of the field-magnets. The field-magnets of continuous current machines are most frequently two-pole or four-pole magnets, whereas those of alternate current machines are usually multipolar.

Fig. 111 shows diagrammatically the arrangement of field-magnets and armature coils adopted in many alternate current dynamos. The field-magnets *N S*, *S N*, &c., are simple solenoids with iron cores bolted to iron frames and facing one another with opposite poles; the lines of force will therefore run straight across the gap from *N* to *S* in each case. Also the lines between alternate pairs of poles run in opposite directions. The armature coils, 1, 2, 3, &c., pass between these poles in the direction shown by the dotted arrow. Thus coil 1 is just leaving a field in which the lines run from back to front; coil 2 is leaving a field in which they run from front to back; coil 3 one in which they run from back to front, and so on, alternately round the armature. These coils have, therefore, at the instant considered, alternately counter-clockwise, and clockwise E.M.F.'s set up in them, as shown by the dark arrows; but by winding alternate coils in opposite directions, as in the figure, all these E.M.F.'s will tend to drive currents round the armature in the same direction. The method of joining these coils to the collecting rings, as they are called, is delineated in Fig. 112, in which the field-magnets are removed. The connecting wires are brought along the axle of the rotating armature, and are respectively joined to the two rings on which the brushes slide.

Returning to Fig. 111, when coil 1 has advanced to the position of coil 2, coil 2 to that of coil 3, and so forth, the current will be in the opposite direction round the armature and in the external circuit, the change occurring when the revolving coils are directly between the poles.

In other dynamos of this type the armature coils are fixed, and the field-magnet poles are rotated past them, thus inducing alternate currents.

In another form of alternate-current dynamo the armature coils are disposed with their axes radial, as in Fig. 109, and are revolved past the poles of a multipolar field-magnet. These and others will be described fully further on.

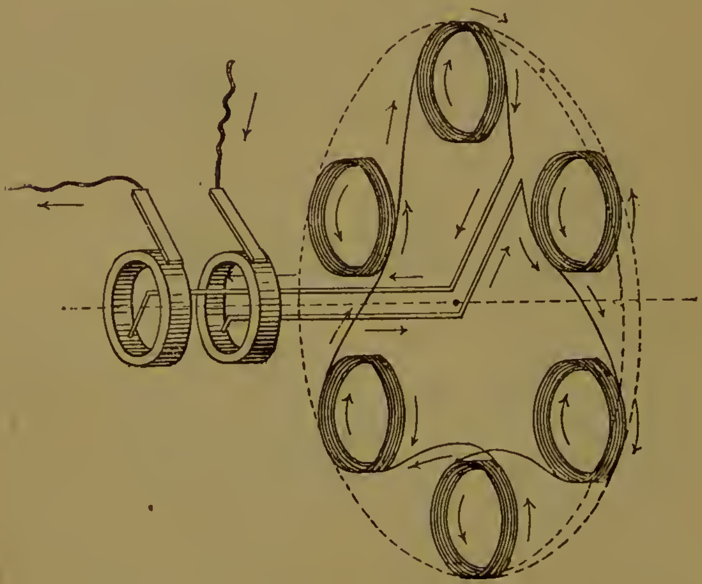

Fig. 112.—Collecting Rings of an Alternate Current Armature.

The Field-Magnets.—From the armature we pass to the other important part of the dynamo-machine, namely, the *field-magnet.* The function of this part of the machine is to produce the magnetic field, which causes induced E.M.F.'s and currents in the armature coils on account of the relative motion.

The field-magnets may be either permanent steel magnets or soft iron electro-magnets, but in all large modern machines the latter are used, because of the greater magnetisability of soft iron compared with steel (*see* page 153). The disadvantage of electro-magnets is that they lose nearly all their magnetism when the current is stopped; it is therefore necessary to maintain an *exciting current*, as it is called, in their coils, and this requires a continuous expenditure of energy caused by the *heating* effect of the current on the wires conveying it. It should be carefully noted that the energy is not used up in maintaining the "magnetism," but that its dissipation is due to the *electric* resistance of the wires. The *same amount of heat* would be produced, and the same expenditure of energy required, if the same current were sent through the same wires coiled so as to give no resultant magnetic effect.

In large electro-magnets the energy expended in maintaining the exciting current is sufficiently large to make its reduction to a minimum a matter of practical importance. We must, therefore, so dispose our copper conductors and iron cores, &c., as to produce, where it is wanted, the strongest possible field with the least expenditure of excitation energy. One of the greatest differences between recent dynamos and those built six or seven years ago is in this direction.

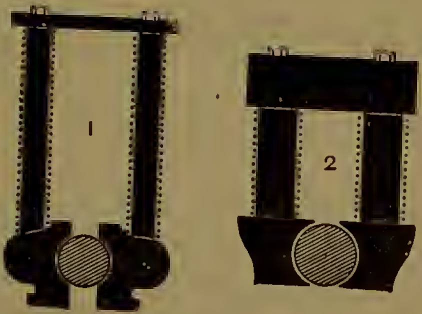

Fig. 113.—Bad and Good Forms of Field Magnets.

The difference between a well and a badly designed field-magnet will be readily appreciated by comparing **1** and **2** of Fig. 113. The thick black parts of both figures represent the iron portions of the field-magnets of dynamos. In **1** the magnetic circuit (or path for the magnetic lines) is unnecessarily long and the iron is thin and insufficient in quantity. In 2 the magnetic circuit is short, and contains an ample supply of iron to convey the magnetic lines. In both figures the positions of the exciting coils are shown in section by dots ranged alongside the enclosed iron.

In well-designed electro-magnets the reluctance of the magnetic circuit should be as small as possible, and the exciting coils should be so placed as to give the requisite magnetomotive force with the least possible production of wasteful heat. In order that the reluctance of the magnetic circuit should be small, we must choose the material carefully, and also dispose of it to the best advantage. The following simple rules indicate the considerations involved :—

(1) The iron part of the circuit should consist of material of high magnetic permeability, such as well-annealed soft wrought iron.

(2) The cross-section of the iron perpendicular to the direction of the magnetic lines should be ample, so that the number of lines per unit area may not be too great.[1]

(3) The length of the circuit in the direction of the lines should be as short as possible.

(4) Any necessary air-gap should be made as narrow as possible in the direction of the lines. The mechanical joints in the iron should be no more than the conditions of economical manufacture render necessary, and the surfaces of each joint should be carefully fitted together.

But in addition to keeping the magnetic reluctance low, we have to remember that the energy used up in wasteful heat should not be more than is absolutely necessary. Now, the object of the electric circuit is to produce a magnetomotive force sufficient to overcome the reluctance of the magnetic circuit and cause a certain flux of magnetic lines round it. The magnetomotive force is proportional to the product of the current and the number of times it is linked through the magnetic circuit, or to put it shortly, it is proportional to the ampère-turns; it is independent of the electric resistance of the copper. But the waste heat is directly proportional to this latter resistance, which is increased by increasing the length of the copper circuit. Thus a large loop gives us no more magnetomotive force than a small one, but with the same current and gauge of copper wire wastes more energy in heat. We should, therefore, keep the coils as close as possible to the iron, and not coil them up in many layers; to do this and also get on the requisite number of coils would require a long length of iron, which, in order that the loops should be small, should not have a great cross-section. Both these conditions are antagonistic to rules (2) and (3) given above, and therefore the final design must be a compromise, in which the conflicting conditions are so balanced as to give the best attainable result. As regards the shape of the cross-section of the iron where the coils are wound, one remark may be made: the circle being the geometrical figure that encloses the greatest area for a given perimeter, the cores of the coils should be of circular section, or as nearly approaching thereto as mechanical considerations permit.

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[1] Numerical data are given in Part II., Chap. VIII.

We shall now illustrate the above remarks with a few examples of the field-magnets of modern dynamo machines. The fact that the conditions for good design are fairly simple has led to an almost infinite variety of modifications in detail, from which, of course, we can only select some of the most typical cases. In our remarks on armatures we have been tacitly referring to a large but by no means exclusive type of field-magnets, namely, those possessing only two-poles. No. **2** of Fig. 113 and Nos. **1** to **4** of the accompanying figure (114) illustrate widely used types of these two-pole

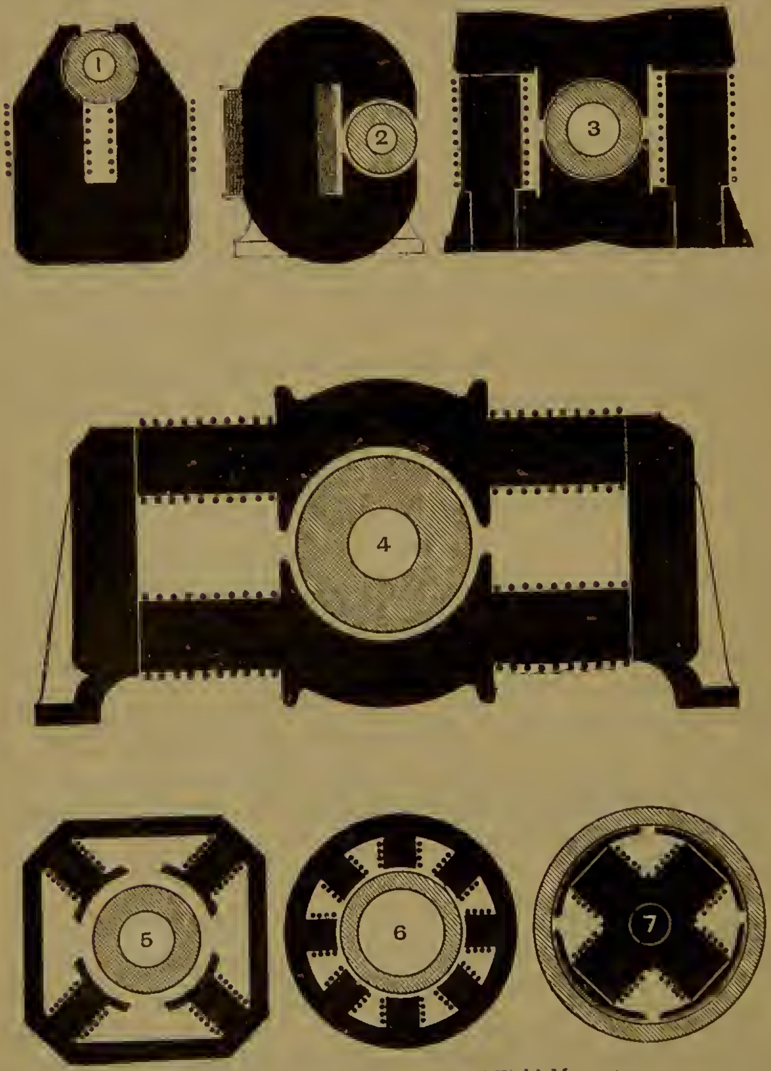

Fig. 114.—Some Typical Forms of Field-Magnets.

machines. In all these figures the iron of the field-magnets is shown in black and that of the armature in light shading, whilst the position of the magnetising coils is shown by dots on either side of the cores. No. **2**, Fig. 113, and Nos. **1** and **2**, Fig. 114, are machines with *single* magnetic circuits; in other words the lines of magnetic flux flow in one general direction through the iron of the field-magnets. In Nos. **3** and **4**, however, there are two general paths for the magnetic lines in the iron of the field-magnets. In both cases the lines can be assumed as travelling vertically downwards through the armature, then deviating to the right and left to the vertical side cores or yokes which they ascend, and again turning inwards, re-unite in the pole-piece above the armature.

The other three diagrams of Fig. 114 represent *multipolar* machines. In Nos. **5** and **6** the poles are turned inwards towards the rotating armature and the exciting coils are wound on them. These poles are alternately **N** and **S**; the magnetic lines, emerging from one of the **N** poles, enter the iron of the armature and divide right and left, travelling through the iron till they reach the adjacent **S** poles, which they enter and complete the magnetic circuit through the yoke at the back. In No. **7** the field-magnet, a four-pole one, is very compact, and lies *inside* the armature which rotates round it. This is a form constructed by Messrs. Siemens and Halske, and illustrates in a striking manner the great adaptability of the simple principles involved in dynamo construction to variations in details.

THE SELF-EXCITING PRINCIPLE.

The earlier dynamo machines in the majority of cases used permanent magnets to set up the field in which the armature revolved; but permanent magnets are not nearly so powerful as electro-magnets of the same size, and therefore, in order to produce the same output of electric energy, the machines had to be very much larger and heavier. In some cases electro-magnets were used, but these were energised by currents from separate current generators, which were sometimes batteries and sometimes smaller dynamo machines with permanent magnets.

The great advance in the developments of dynamo-electric machinery during the last sixteen years has been due in large measure to the discovery that *the machine itself can be relied upon to supply the exciting current to its own field-magnets.* We have already (page 155) referred to the fact that even the softest and magnetically best wrought-iron retains *some* trace of magnetisation when withdrawn from the magnetising field or when the magnetising field is suppressed by the cessation of the current which gives rise to it. What is true of a mere bar of iron, which when magnetised has to complete its magnetic circuit through the air, is still more true in such magnetic circuits as we have just been considering in the case of the field-magnets of dynamo machines. Indeed, it may be enunciated as a general principle that, provided no change is made in the quality of the iron, *the better the form of the magnetic circuit the greater is the permanent magnetisation it can retain.* Even in a badly designed dynamo it is found that there is always sufficient *residual magnetism*, as it is called, to start the action, which is usually described somewhat as follows. The residual magnetism of the field-magnets sets up a weak magnetic field, and when the armature is spun in this field, small E.M.F.'s are set up which give rise to small currents in the circuits provided. These currents, or part of them, being led through the coils of the field-magnets, increase the magnetism of the field, which then gives rise to greater E.M.F.'s and currents; the latter still further increase the field, giving rise to a further increase of current, and so on, and this action and re-action continues according to a kind of compound interest law until the iron of the field-magnets becomes saturated and no further increase is possible. This represents fairly well what actually takes place, with the exception of the cause assigned for the cessation of the mutual increase, which—as we shall see presently—is only partially true. At first this *building-up power* of the residual magnetism was not very confidently relied upon, and it was customary with some people to start the action of the machine by first sending a comparatively small current from a primary battery through the coils of the field-magnets. This is, however, quite unnecessary.

The next point to consider is how the electrical connections are made so as to send a sufficient exciting current round the coils of the field-magnets of the machine. It must be remembered that the magnetomotive force of a current circulating in the wires of a solenoid is proportional to the product of the current by the number of times it passes round the axis of the coil. Thus, a weak current passing many times round gives as great a magnetomotive force as a strong current passing a few times round. It is not surprising, therefore, to find that both these methods of obtaining the requisite magnetomotive force and combinations of them are employed in dynamo machines. We may distinguish three principal classes :—

(1) **Series**-wound machines, in which large magnetising currents are used.
(2) **Shunt**-wound machines, in which small magnetising currents are used.
(3) **Compound**-wound machines, in which the two former cases are combined.

Lest it should be imagined that the employment of weak currents leads to a less production of wasteful heat in the coils (page 211), we must remind our readers that with a given disposition of the coils and the use of the same volume of copper wire, the heat wasted in maintaining a given magnetomotive force is independent of the actual current used. We proceed to describe the electric connections required in the above three cases.

The Series Dynamo.—In this machine the *whole* of the current which passes through the outer circuit is sent through the field-magnet coils. The connections for doing this are shown diagrammatically in Fig. 115. One of the brushes is permanently joined to one end of the magnetising coil, the other end of which is soldered to the binding screw which forms one terminal of the machine. The other brush is permanently connected to the other terminal, and the ends of the outer circuit are made fast to these two terminals. The figure shows the positive brush, *i.e.*, the brush *from* which currents flow, joined to the field-magnet coil, but whether the connection is made to the positive or the negative brush is immaterial, for *the current is the same in all parts of a simple circuit* such as is here depicted. The armature is supposed to be rotating clockwise, and the arrows show the direction of the current in the circuit. Since the whole of the current is led round the field-magnets, it is only necessary to send it round a few times, but the conducting wires used must be thick enough to carry this current without becoming inconveniently hot. It should be noticed that no current flows until the main (external) circuit is closed, and therefore, although the

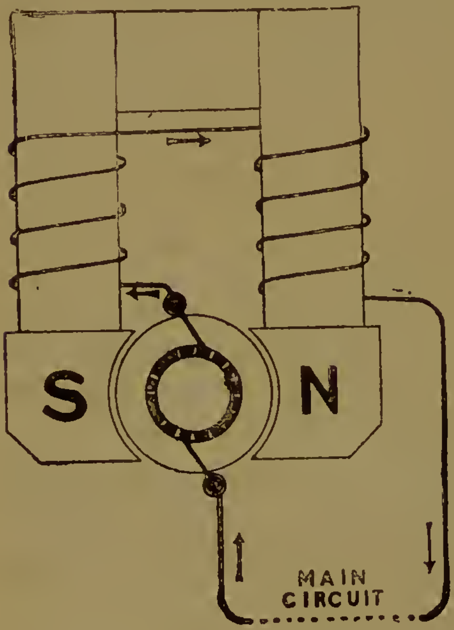

Fig. 115.—The Series Dynamo.

armature may be rotating at full speed, the potential difference at the terminals is very small until the main circuit is completed and the magnetism of the machine begins to build up.

The Shunt Dynamo.—Here only a part of the current generated in the armature is allowed to circulate round the magnetising spirals of the field-magnets. *Both* brushes are (Fig. 116) permanently connected to the ends of the field-magnet coil, and also to the external terminal screws of the machine. Therefore, when the current reaches the positive brush, it divides into two portions, one of which flows round the field-magnet coils to the negative brush, and the other, usually the larger, flows round the external circuit from one brush to the other, provided this circuit be closed. When a current divides thus between two paths, one path is said to be a *shunt* to the other, hence the name given to this form of winding. As the current flowing round the field-magnets is so much subtracted from the current available for useful work in the external circuit, it is made as small as possible consistent with the development of the necessary magnetomotive force. It is therefore necessary to lead it *many times* round the iron of the field-magnets, and for this

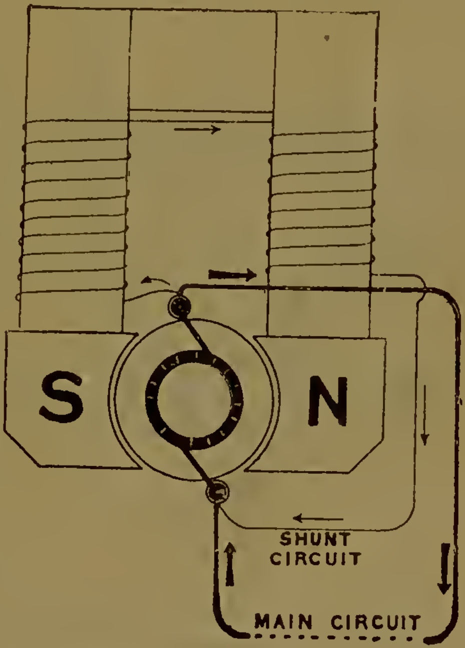

Fig. 116.—The Shunt Dynamo.

purpose spirals wound with *fine* wire are obviously the best. The directions of the two sets of currents are shown in the figure by light and dark arrows, the armature rotating clockwise as in the last figure. In shunt dynamos there is always a closed circuit in connection with the brushes; and therefore, whenever the armature is running at the proper speed, the field-magnets are fully excited and the full E.M.F. of the machine is developed whether the outer circuit is closed or not. In this respect they differ essentially from series dynamos.

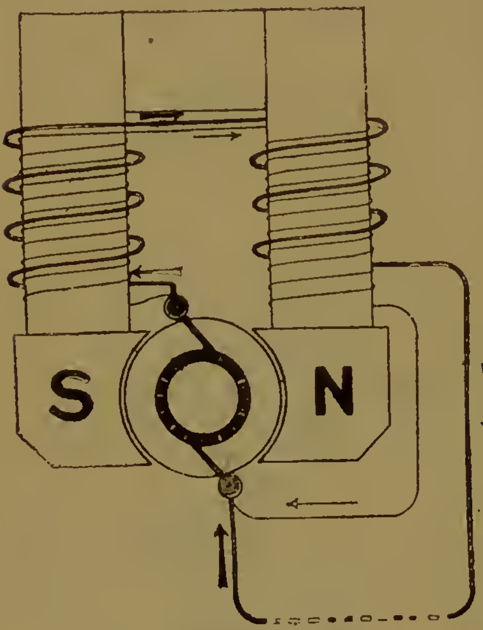

Fig. 117.—The Compound Dynamo (Short Shunt).

The Compound Dynamo is a combination of the preceding methods of winding. The external, or the whole armature, current is led a few times through thick spirals round the field-magnets, and in addition a small shunt current in a fine wire shunt circuit also passes many times round. There are two ways, illustrated in Figs. 117 and 118, in which this may be done. In Fig. 117 the two ends of the fine wire magnetising coil are joined directly to the brushes as in Fig. 116, and the whole of the *external* current passes round the thick magnetising spirals. On the other hand, in Fig. 118 the ends of the fine wire magnetising circuit are joined to the external terminals of the machine instead of to the brushes, and the whole of the *armature* current passes round the few thick magnetising coils. The first method is known as "short shunt" and the second as "long shunt" compound winding.

The Separately-Excited Dynamo.—In the above cases we have tacitly assumed that the dynamo was a continuous-current one, and that the currents drawn from its collector by the brushes were unidirectional. Such currents must always be employed to produce the field required in a dynamo machine. If therefore the dynamo delivers alternate currents into the external circuit, these currents cannot be used to excite its own field-magnets, which must therefore be supplied with a continuous current from a separate source or generator. For large alternate-current dynamos this is usually a small continuous-current machine placed alongside and worked by the same engine, or where there are several alternators (*i.e.*, alternate-current dynamos) in the same place, their field-magnets may all be excited by the current from one continuous-current dynamo.

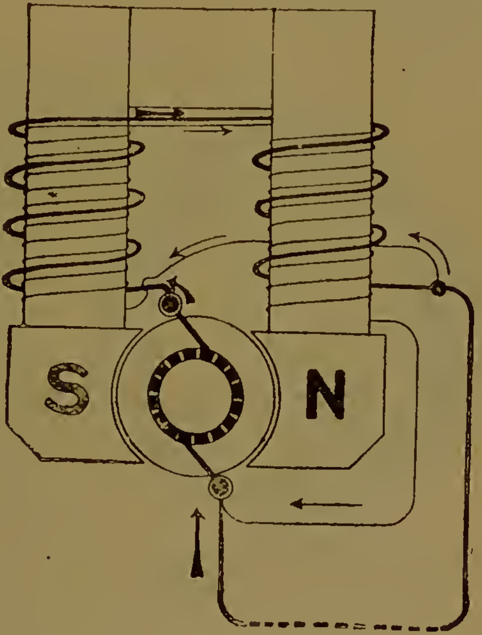

Fig. 118.—The Compound Dynamo (Long Shunt).

In some alternators a few of the armature coils are connected to the bars of a commutator which delivers a unidirectional current from these particular coils to a pair of separate brushes, whence it is led through the circuit of the field-magnets. The main current of the machine is taken from the remaining coils to connecting rings, and led into the external circuit as an alternate current.

Continuous-current dynamos might also have their field-magnets excited by currents from a separate source, though this is not now usual, except as an auxiliary for purposes of regulation.

Reactions in the Armature.—Returning to the case of the two-pole dynamo with a Gramme ring armature (Fig. 107), we have now to consider briefly the effect of the current in the armature upon the field due to the field-magnets. So far we have neglected this, and have assumed that the magnetic field in which the coils revolve remains unchanged when heavy currents are drawn from the armature. Obviously this is not the case, for the passage of the armature current converts the *armature* into an *electro-magnet*, whose presence must affect the magnetic field. For a reason to be explained presently, the brushes in Fig. 107 are not set on the vertical diameter, but are moved a few degrees forward in the direction of rotation. Suppose *A* to be directly over these brushes, the armature currents will flow as marked by the arrows in Fig. 107. A simple application of the corkscrew rule will show that these currents will magnetise the iron of the ring, so that a North pole is formed at *A* and a South pole at *B*. The lines of force

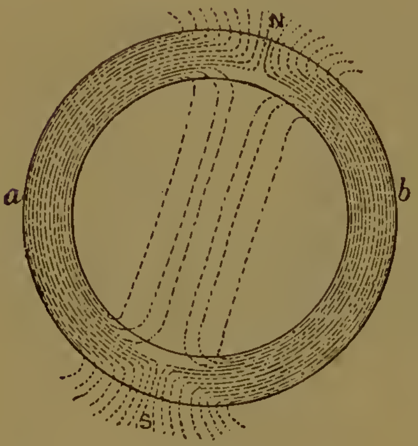

Fig. 119.—Lines of Force due to the Current in the Armature.

due to the *ring alone* will run out from the iron at *N* (Fig. 119), and into it again at *S*. This armature field is superposed upon the field due to the field-magnets, the latter causing lines to enter the iron round a considerable length on the right and leave it round a similar length on the left. The effect is that a resultant field is produced, which is shown diagrammatically in Fig. 120 and as mapped out by iron filings in Fig. 121. The original field, due to the field-magnets alone, is twisted round in the direction of the rotation, and at the same time, according to the general law (Lenz') of such reactions, is rendered weaker. The field being thus distorted, the neutral position in which the coils have no induced E.M.F. in them will no longer be on the vertical diameter, as assumed in Fig. 107, but will be moved forward in the direction of rotation. This forward set of the brushes is known as the *lead*, and is necessary if the machine is to run without sparking at the

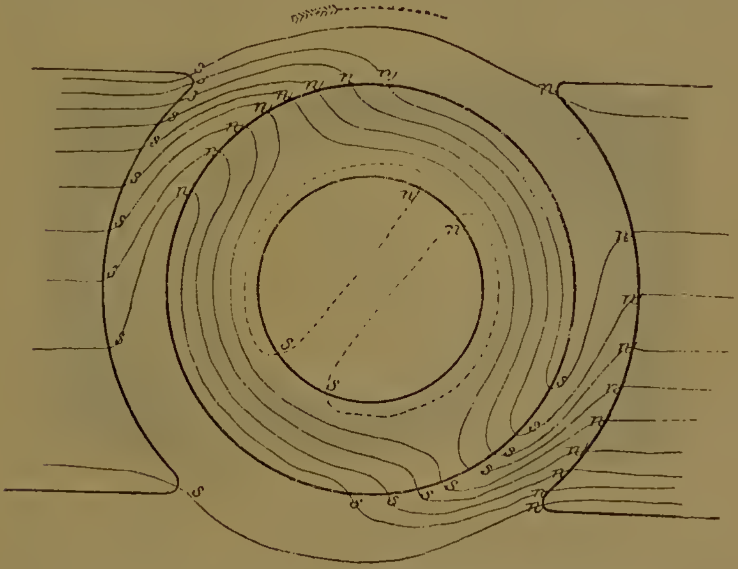

Fig. 120.—Twisted Field due to Magnetic Re-action of Armature.

brushes. The chief reason for the forward lead is that just given, but in practice the lead has to be increased a little more because of other minor reactions.

Losses in the Armature.—It may not be without interest to our readers if we briefly indicate the different ways in which energy is lost in an armature, for these illustrate, from a practical standpoint, the importance of some of the least generally known laws of magnetic and electric phenomena. First, there is the loss due to the heating effect of the current in its passage through the armature coils. This can be reduced for a given current only by reducing the electrical resistance of the armature coils, by shortening the length of the wire and increasing its cross-sectional area. These conditions are, however, antagonistic to the production of high E.M.F.'s, and therefore can only be partially met. Secondly, there is a loss of energy due to magnetic hysteresis. The current in the armature coils, and therefore the magnetism of the iron core, is being continually reversed, and with each complete cycle of magnetisation we have an amount of energy wasted

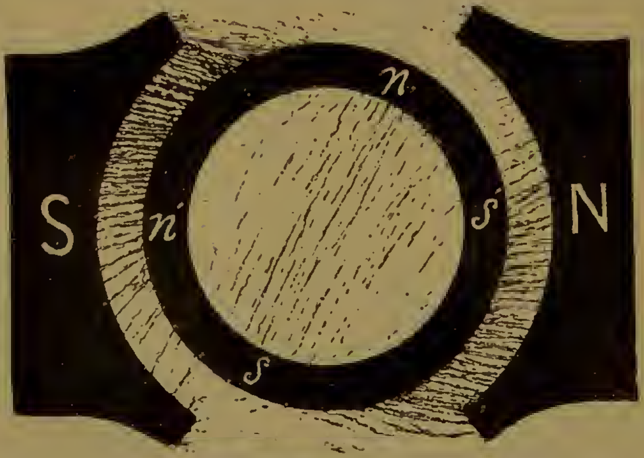

Fig. 121.—Twisted Field as shown by Iron Filings.

proportional to the area of the hysteresis loop (page 155). Hence another reason for using good wrought iron for the armature coil, as its hysteresis loop is much less than that of cast iron or steel. Lastly, there is the loss due to the formation of "Foucault" or "eddy" currents in the iron of the armature. This is reduced by lamination, or the splitting up of the iron with insulating material, across the direction in which the currents tend to flow. Thus the iron of the armature is either made up of thin flat rings slipped on to the axle of the machine and separated from one another by sheets of paper or other material, or consists of a bundle of iron wires, each separately varnished, and coiled up into the required form. For example, in the Siemens armature (Fig. 108) the drum on which the copper wires are wound consists of two thick gun-metal cheeks fixed on the axle at the two ends. These carry an inner projecting rim, upon which a thin sheet of iron is wrapped, and over this is coiled a quantity of soft iron wire, carefully varnished. The eddy currents tend to circulate in directions parallel to the outer copper wires, but in this direction the iron is discontinuous, and offers no conducting electric circuit.

We thus see how necessary it is in the design of a dynamo machine to be thoroughly acquainted with, and to allow for, the more recondite effects which careful research has proved to be always present when certain conditions are fulfilled.

Historical Notes.

As we have now described in some detail the chief points of interest in typical dynamos, we are in a position to indicate briefly the lines along which development proceeded in the interval which bridged the gap between Faraday's fundamental discoveries and the evolution of the modern dynamo machine. One of the most curious points that cannot fail to strike even a careless student of the history of this development, is the frequency with which various important details have been invented and re-invented independently by different constructors. Over and over again an important step in advance has been made, and buried either in the transactions of some learned society, or in the current scientific literature, or even in the Patent Office, and thus consigned for a time to oblivion. Then ten, fifteen, or twenty years later another worker, quite independently, discovers the same thing over again, and in perfect honesty puts it forth as an original discovery; this time, however, it bears the fruit which it should have borne before, and its importance becomes widely recognised.

To take only one example. The self-exciting principle (*see* page 213) was suggested independently by Jacob Brett and by Hjorth in 1848, and by Sinsteden in 1851. It was re-invented by Baker and by Varley in 1866, and again independently by Wheatstone and by Siemens in 1867. Other inventors also appear to have made use of it, and yet some years elapsed, even after 1867, before the principle began to be generally used and its importance recognised. Several other instances might be given, did space permit, of the arrested development, as it were, of essential details of the modern dynamo; but we must pass on, merely remarking that in other branches of science the same phenomenon has occurred.

Faraday's discovery of magneto-electric induction quickly bore fruit in the shape of machines for producing electric currents. Both Dal Negro and Pixii devised such machines in 1832, a few months after the publication of Faraday's researches, and the latter even employed a commutator to convert the alternate into uni-directional currents. In the few following years many inventors worked at the subject, but all used permanent magnets. We may mention especially, however, the work of Sturgeon, who in 1838 invented the split-tube commutator, and that of Woolrich, of

Birmingham, who in 1844 constructed the first magneto-electric machine which appears to have been used commercially, in this case for electroplating. Woolrich's historical machine is shown in Fig. 122. Four large permanent horse-shoe magnets were arranged on a strong wooden frame with their poles pointing inwards. Between these four pairs of poles there rotated an armature with eight separate coils. Since there were twice as many coils as pairs of poles, it follows that at any instant the induced currents in four of these coils would be in one direction and those in the other four in the opposite direction. By an ingenious system of connections and using three brushes, Woolrich led these two different sets of currents into two

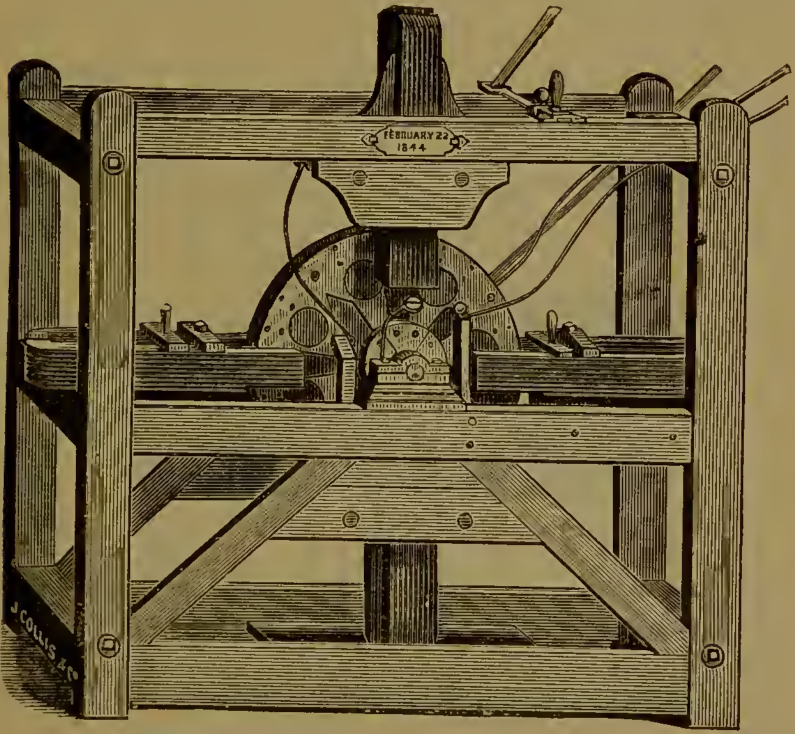

Fig. 122.—Woolrich's Electroplating Dynamo.

separate circuits, each containing plating baths. And the brushes and commutator bars were so arranged that, when the directions of the induced currents in the coils changed, the connections to the outside circuits were automatically interchanged, and thus the currents in the latter were always unidirectional.

Wheatstone worked at the subject from 1841 to 1845, and in the latter year, in conjunction with Cooke, he patented the use of electro-magnets—not, however, self-excited.

In 1856 Siemens invented the shuttle-wound armature which is shown in Fig. 123, and which played an important part in many subsequent machines. In conjunction with a two-part commutator it is just the simple loop of Fig. 101, with many turns of wire instead of a single turn. Meanwhile great attention was being paid in France to the design of alternate-current machines with permanent magnets for the purpose of supplying current to arc lamps in lighthouses. As the result of a great deal of work by Nollet, Holmes, and others, extending from 1849 to 1863, there was produced the "Alliance" machine (Fig. 124), which, until quite recently, held its ground well for this class of work. We must not here omit to mention the important series of machines patented by Wilde, of Manchester, between 1861 and 1867; in the larger of these

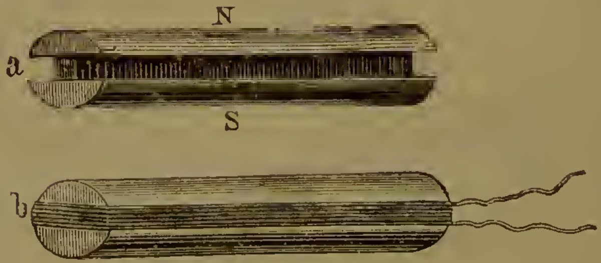

Fig. 123.—Siemens' Shuttle-wound Armature.

(Fig. 125) the field-magnets were electro-magnets excited by a much smaller machine that had permanent steel magnets M M, shuttle-wound armatures being used. Some of Wilde's machines were the most powerful that had been constructed up to that time.

We now come to the end of the year 1866 and the beginning of 1867, when three separate inventors, independently and almost simultaneously, described practical machines in which the self-exciting principle was used. The first in point of time seem to be the brothers Varley, who in December, 1866, patented such a machine. Then on January 17th, 1867, Werner Siemens described to the Berlin Academy a machine with series-wound electro-magnets excited by the current from the machine itself.

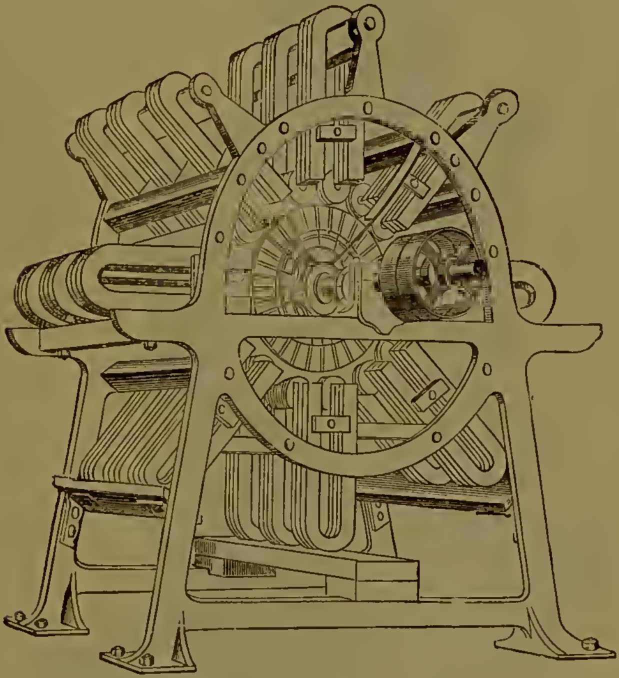

Fig. 124.—The Alliance Machine.

And on February 14th, the same day that Siemens' paper was brought to the notice of the Royal Society of London, Wheatstone read a paper before the Society describing a

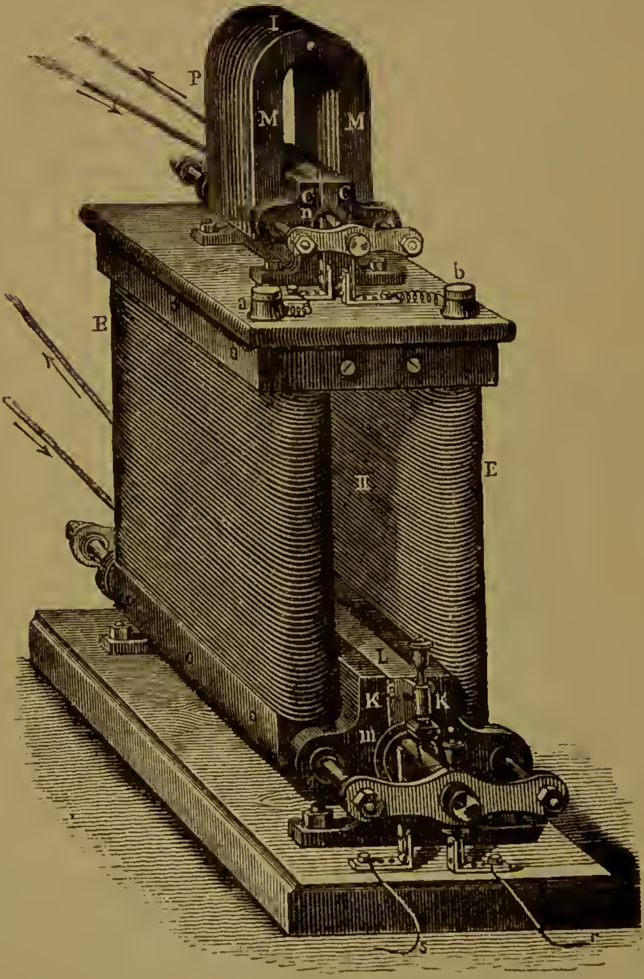

Fig. 125.—Wilde's Machine.

similar machine, but with shunt-wound electro-magnets. Siemens' paper is made doubly interesting from the fact that in it the term *dynamo-electric machine* was first introduced to the world. Thus the two chief ways of exciting the field magnets were published in England at the same time. The combination of these, the compound winding (page 218) was invented by Varley in 1876, and has been the subject of a recent heavy lawsuit.

The next great step was the invention by Gramme, in the year 1870, of the continuous ring method of winding the armature; but here again the method had been previously invented in a slightly different form by Pacinotti in 1864. Three years later, in 1873, Von Hefner Alteneck applied the principle of the Gramme ring to the old shuttle-wound Siemens armature, and thus introduced the drum armature, which is now so largely used.

From these inventions the development of the modern dynamo starts; subsequent inventors have confined themselves to improvements in the design and arrangement of the various parts of the machine, but these improvements, though very important in producing the highly efficient machines which we now possess, are chiefly of a highly technical character, and are therefore of more interest to the electrical engineer than the general reader. One exception we should, however, make, for no sketch of the history of the dynamo would be complete without a reference to the work of Dr. Hopkinson, who in 1883 showed that it was very important to consider carefully the design of the magnetic circuit of the machine, as well as that of the electric circuits. This part of the subject has already been dealt with pretty fully.

MODERN CONTINUOUS-CURRENT DYNAMOS.

Passing now from our brief historical survey, we propose to describe a few of the main types of modern dynamo machines, which for convenience we shall divide into two classes only, namely, "continuous-current" dynamos, and "alternate-current" dynamos, or as they are now more briefly called, "alternators." It has already been remarked that there is almost an infinite number of ways of fulfilling the fundamental conditions for the production of electric-current energy from mechanical energy by means of dynamos. Nevertheless, practice and theory combined have gradually evolved, by a process of "survival of the fittest," a few leading types which in reality hold the field, and many of the mechanical and electrical monstrosities produced in the early days of the development have been literally shouldered out of existence by their more sturdy competitors.

But though the types of machines that have survived are not very numerous, they are built by a great number of manufacturers, and thus the task of selecting a few for description is somewhat invidious. We wish it therefore to be understood, that in describing a few machines we do not intend it to be inferred that those left undescribed are in any way inferior in design or efficiency. Considerations of space and of our readers' patience alone prevent us from making the list much longer.

The first machine we propose to describe is one belonging to a class now extensively built. It is known as an "overtype" machine, from the fact that the armature is at the top, and that the field-magnet cores rise from the bed-plate, which serves as a magnetic yoke. The particular machine illustrated (Fig. 126) is one built by Messrs. Patersen & Cooper, and known as the "Phœnix" Dynamo. The iron cores of the field-magnets, surrounded by their magnetising coils C, are bolted to the massive cast-iron bed-plate B. On the top of these cores are the pole-pieces P, hollowed out to receive a ring-wound armature; the magnetic circuit is thus similar to that depicted in No. 1, Fig. 114. The commutator *c* is a large one, and the strips *s* connecting its various segments to the windings of the armature can be plainly distinguished. The brushes *b b* are mounted on a rocker by means of which their position in the commutator can be adjusted to the proper "diameter of commutation" whilst the machine is running. The tips of the brushes should always lie on opposite ends of a diameter, but if this diameter is far from the "neutral" position there will be a good deal of sparking at the brushes. When this occurs, the rocker must be moved round until a position is found at which the sparks disappear.

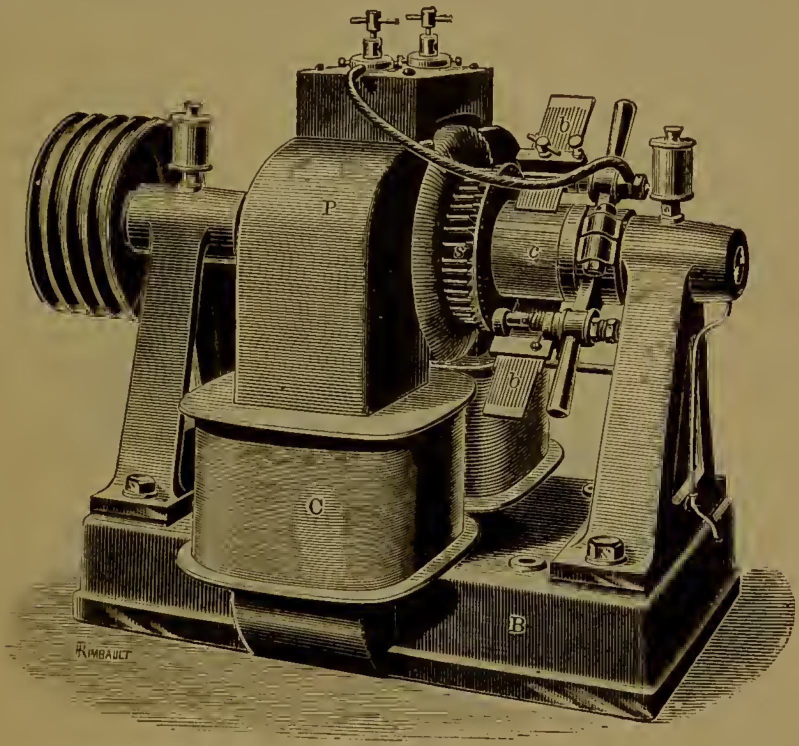

Fig. 126.—The "Phœnix" Dynamo.

The field-magnets of the machine are compound-wound, so as to produce the same potential difference at the terminals for wide variations of load. It may interest our readers to know the actual resistances of the various electric circuits of such a machine. In a dynamo of this kind designed to give 180 ampères at 105 volts, or 24 electric horse-power,[1] the resistances are:—Armature 0·02 ohm, series winding of field-magnet 0·01 ohm, and shunt winding of field-magnet 29·5 ohms. Comparing these resistances with those given for batteries (pp. 53 and 58), one realises how enormously superior the dynamo is even in this respect to the best forms of batteries, for it must be remembered that low internal resistance means small loss of energy in wastefully heating the current-producer itself.

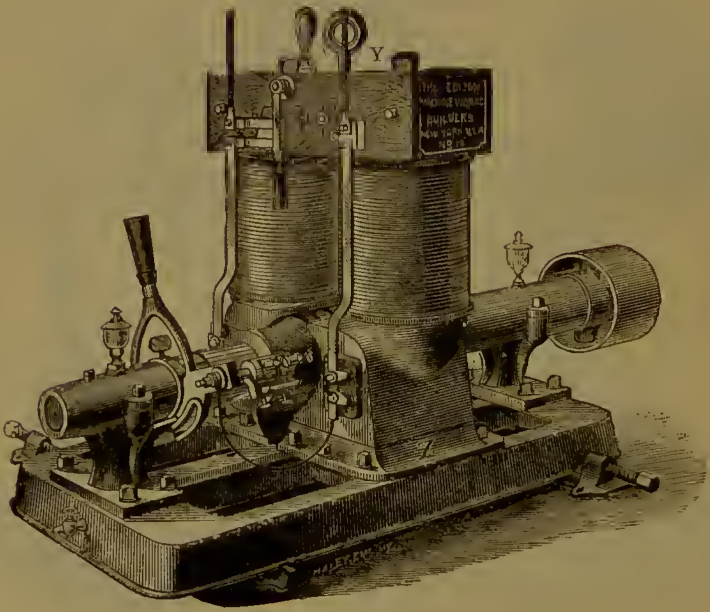

Fig. 127.—The Edison Dynamo (1888 type).

The next machine (Fig. 127), an Edison dynamo of modern type embodying Dr. Hopkinson's improvements, is magnetically the preceding one turned upside down. The pole-pieces and armature are at the bottom of the machine, and a massive yoke (Y) joins the top ends of the field-magnet cores, the magnetic circuit being similar to that sketched in No. 2, Fig. 113. One magnetic difficulty necessarily occurs in machines of this type. Iron is practically the only suitable material for the greater part of the bed-plate on which the dynamo rests; but if the pole-pieces were directly supported on the iron bed-plate, most of the lines of magnetic force set up by the magnetising coils would pass from one pole-piece to the other through the iron of the bed-plate instead of through the gap in which the armature lies, and where their presence is essential to the working of the machine. To reduce this magnetic "leakage," as it is called, as much as possible, a high foot-step Z of zinc is interposed between the iron of the pole-pieces and that of the bed-plate; but notwithstanding this precaution a considerable percentage of the total lines set up complete their circuit through the bed-plate, and these are useless.

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[1] This term is explained later (page 408).

The machines, which are built in the United States and are intended for incandescent lighting, have drum-wound armatures, the field-magnets are shunt-wound, the bearings are long, and there are good mechanical arrangements for holding and rocking the brushes. They vary in size from 15 inches high, capable of delivering 3½ horse-power electrically, to 182 inches high, giving 200 horse-power.

There is still another type of "single magnetic circuit" dynamo, in which the armature is placed neither at the top nor at the bottom, but about half-way up. The design was originated by Dr. S. P. Thompson in 1886, and has been independently devised by several constructors. The magnetic circuit is sketched in No. 2, Fig. 114. The particular machine illustrated (Fig. 128) is constructed by Messrs. Greenwood and Batley, of Leeds, and is known as the "Leeds" Dynamo. There is only one magnetising coil on the field-magnet, and the bed-plate is usefully employed for part of the magnetic circuit; in fact, the lower pole-piece is part of the bed-plate casting. The armature is a Gramme ring, and the arrangement of commutator, brush-holders, and rocker is good, but calls for no special comment. The type is especially well adapted for small machines, but large ones giving about 50 horse-power electrically have also been built.

We next give an illustration of a machine with a "double magnetic current" of the kind sketched in No. 3 of Fig. 114. The machine illustrated (Fig. 129) was designed by Mr. A. T. Snell for the General Electric Traction Company of London, and is specially adapted for traction and mining work. The arrangement of the magnetic circuit will be understood from what has been already said on page 213. The armature is of the ordinary type, but the details cannot be seen in the figure. The brushes used are of a kind to which we have not hitherto referred, being made of solid carbon instead of copper, the butt-ends of the carbon blocks being pressed against the commutator from behind

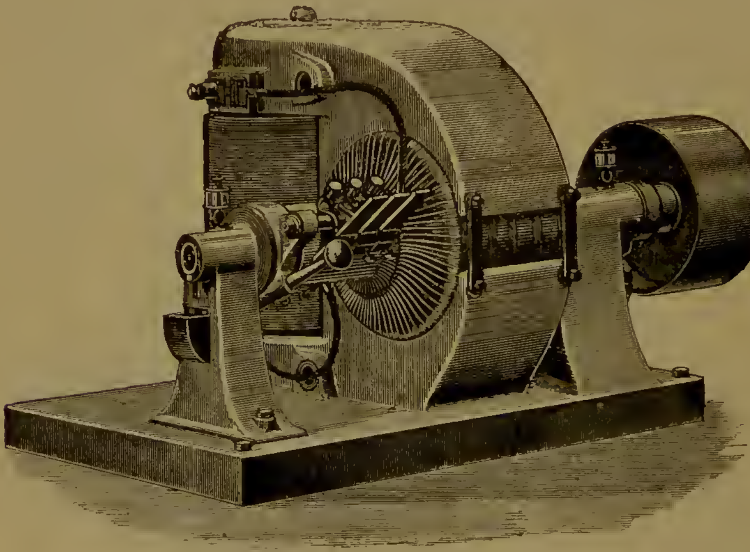

Fig. 128.—The "Leeds" Dynamo.

by spiral springs as shown. Carbon blocks were first proposed for this purpose by Professor G. Forbes in 1885, and have proved very satisfactory, especially for electric motors which have to run both ways.

We shall conclude our illustrations of continuous-current dynamos with a multipolar one, having a magnetic circuit of the general type sketched in Nos. 5 and 6 of Fig. 114, but in this particular case having eight poles to the field-magnets Fig. 130 depicts such a multipolar dynamo designed by Mr. Gisbert Kapp for central station work, and it may be remarked here that, for this particular class of work, machines of the multipolar type have been recently designed by Edison, Siemens, and many other constructors. A comparison of Figs. 113 and 114, and a reference to our remarks on page 213, will enable the reader to understand how the magnetic lines enter and leave the iron of the armature. The magnetising coils and the pole-pieces, extended so as to cover a definite part of the periphery of the armature, can be clearly traced

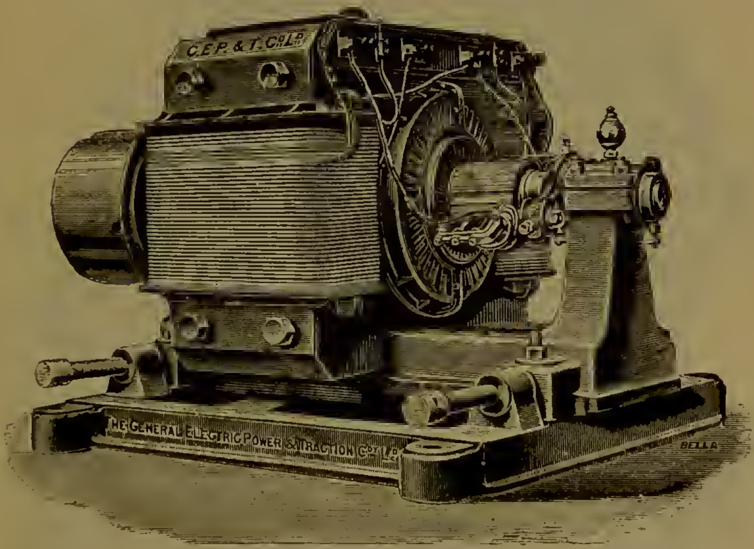
C.E.P. & T. Co. L^D.
THE GENERAL ELECTRIC POWER & TRACTION Co. L^D.
BELLA

Fig. 129.—The Snell Dynamo.

in Fig. 130. The armature is not very long, but has a core 48 inches in diameter, and a massive commutator of 181 segments which slides under two sets of brushes at an interval of 135°. The brushes are mounted in rocking brush-holders, whose position can be adjusted by the hand-wheel and worm-gearing at the side. This machine has an output of 550 ampères at 260 volts, or about 250 electric horse-power.

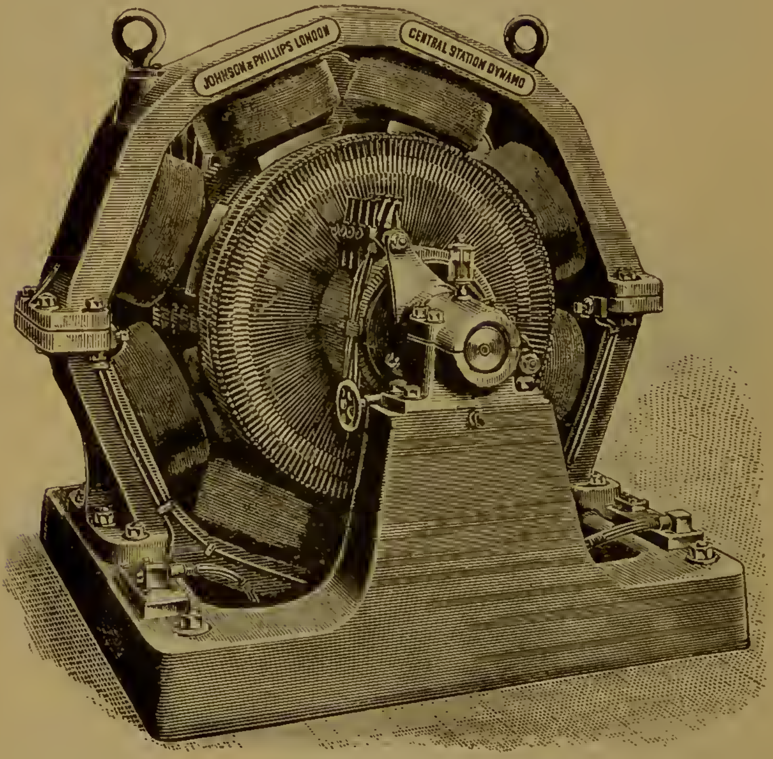

Fig. 130.—Kapp's Multipolar Dynamo.

ALTERNATE-CURRENT DYNAMOS OR ALTERNATORS.

Turning now from continuous-current machines, we propose to illustrate and describe two or three widely used forms of alternate current machines or "alternators." The essential difference between the methods by which the currents are led in the two classes, from the rotating armature into the outer circuit, have been already described on page 197. It may, however, be remarked that in alternators the armature is very frequently the stationary part of the dynamo, and the field-magnets are rotated. In these cases the exciting current is passed into the coils of the rotating field-magnet by means of simple sliding contacts, to which the ends of the coils are connected.

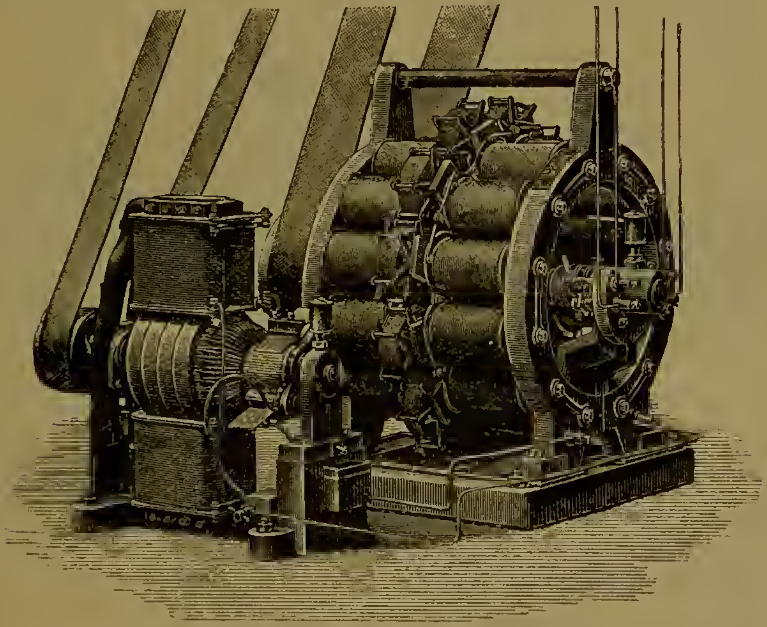

Fig. 131.—Siemens' Alternator with Exciter.

In Fig. 131 is illustrated 'a form of alternator designed as far back as 1878 by Von Hefner Alteneck for Messrs. Siemens and Halske. The armature, which is of the disc kind, depicted diagrammatically in Fig. 112, revolves between the poles of two sets of electro-magnets arranged opposite one another round the circumference of a circle. We have explained the methods of connecting the coils to one another so that all the E.M.F.'s may act in the same direction at any instant in the circuit. The coils of the armature are usually wound upon wooden cores and enclose no iron. They are constructed of ribbons of copper insulated from one another by strips of vulcanised fibre, and are held in their places by the clamps which can be seen in the figure. For a reason already referred to (page 219), the currents of the machine cannot be used to excite its field-magnets, and therefore a small continuous-current machine, placed in front of the larger alternator, and driven by a belt from the same shaft, is used for this purpose. The continuous-current machine depicted is one of the well-known Siemens types. It is a two-pole drum armature machine with a vertical double magnetic circuit. As it is used solely for supplying current to the field-magnets of the alternator, its terminals are permanently joined to the field-magnet circuits by the copper rods seen passing from one machine to the other in the lower part of the figure. The vertical rods on the right-hand side are the conductors by which the currents of the alternator are led away to the external circuits. For very large machines having an output of more than 400 horse-power, Messrs. Siemens use quite a different pattern, in which the field-magnets are rotated inside a large stationary armature.

The next machine illustrated has also a disc armature, but this is firmly fixed to the bed-plate, whilst a multipolar field-magnet, having a single exciting coil, is rotated near it. The full machine, which was designed by Mr. Mordey for the Brush Electrical Engineering Company, is shown in Fig. 132, and it will be noticed that the small continuous-current dynamo for supplying current to its field-magnets is mounted on the same spindle, being carried quite neatly on a side-bracket. The stationary armature is depicted separately in Fig. 133, and the multipolar field-magnet in

Fig. 134. The most curious part of this machine is probably its multipolar field-magnet with its single magnetising coil, to show which clearly, the shield seen in Fig. 132 has been removed. This coil, as can be seen in Fig. 134, encircles the axis of rotation of the magnet, which forms the centre of its coil; the lines of magnetic force set up in this coil pass into the radiating polar projections, which curve round towards one another, and almost meet, the gap between their ends being only about three-quarters of an inch wide. We thus have a series of opposed poles, all those on one side being of North polarity, and all those on the other of South polarity. There are, therefore, very strong magnetic fields in the gaps between the poles, but scarcely any field in the intervening spaces. The field-magnet is so mounted that when it is spun these gaps are occupied successively by the coils of the armature depicted in Fig. 133. In the machine illustrated there are

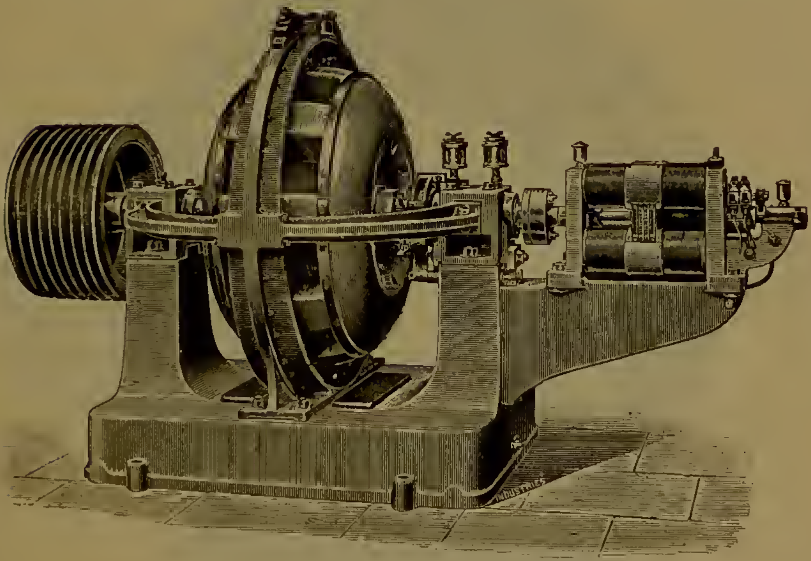

Fig. 132.—The Mordey Alternator with Exciter.

nine narrow gaps in the field-magnet and eighteen coils on the armature. Consequently, as the magnetic gaps sweep round, each coil of the armature is alternately in a strong and a weak field, and thus E.M.F.'s are induced in these coils due to rapid changes in the lines of force passing through them. The armature coils are made of copper ribbon wound upon porcelain cores, and insulated with a thin tape; no metal, except the copper of the coils, enters the magnetic field, and thus Foucault or eddy currents are avoided. The coils, of the shape seen in Fig. 133, are clamped, with proper insulation interposed, to a light gun-metal frame, and if necessary, any coil can be removed for inspection and repair without taking the machine to pieces.

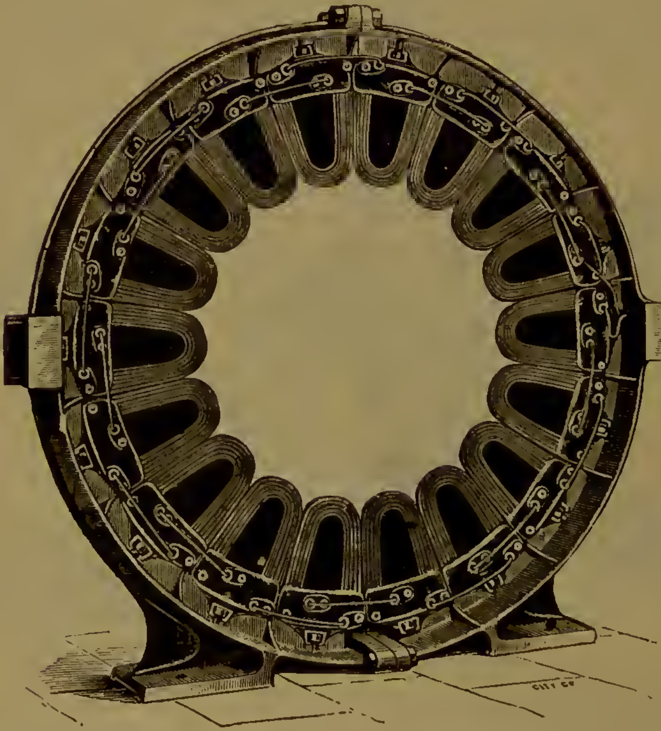

Fig. 133.—Armature of Mordey Alternator.

There are many other ingenious details, both mechanical and electrical, about the machine, which we have not space to describe fully, but which all tend to increase its efficiency.

The largest machine yet built of this type has an output of 500 kilowatts (670 horse-power) and a commercial efficiency of 93 per cent., by which we mean that 93 per cent. of the mechanical power delivered upon the shaft is available as electrical power in the external circuit. It has 80 armature coils and 40 pairs of poles on the field-magnet, which, with the shaft, weighs 40 tons. In the machine represented in Fig. 132, it is interesting to note that the small continuous-current dynamo at the end of the shaft, which supplies the current for the field-magnet, only weighs $\frac{1}{40}$th of the total weight of the machine, and in the larger machine just referred to, the power absorbed by the magnetising circuit is less than $1\frac{1}{2}$ per cent. of the output.

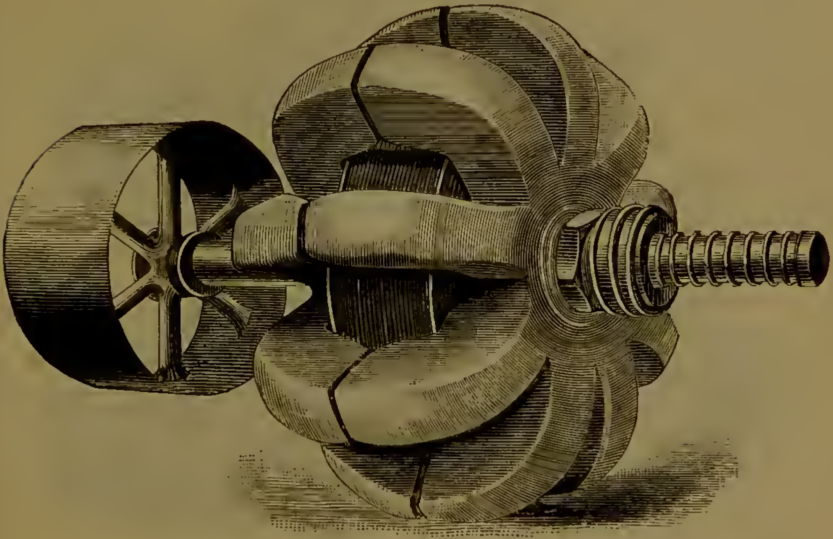

Fig. 134.—Field-magnet of Mordey Alternator.

The last alternator to be described is one constructed by the Westinghouse Company in the United States. It is illustrated in Fig. 135, and instead of a disc armature similar to those of the two preceding machines, its armature is of the drum type. The field-magnet is multipolar, with 16 radial poles projecting inwards from a massive external yoke. The poles are alternately of North and South polarity, and the drum armature revolves in the central space towards which they are directed. The core of this ure is a cylinder built up of thin iron discs, and the coils, after being wound on formers, are laid flat on the periphery of the cylinder, across which the wires of the coils run backwards and forwards. The end loops of the flat coils are bent over the sides of the drum, and the coils are held in their places by insulated binding wires; there

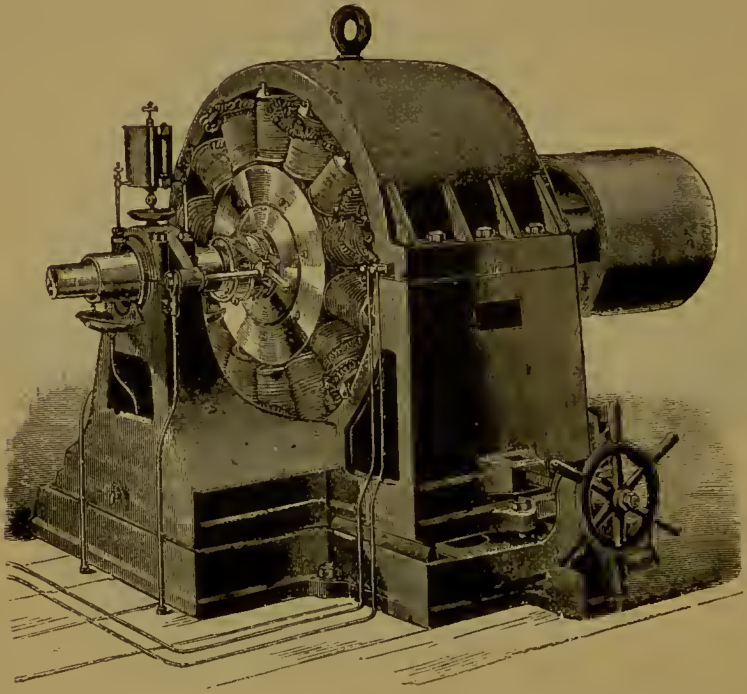
Fig. 135.—The Westinghouse Alternator.

are the same number of coils as magnet poles, and they are usually joined up in two sets of eight coils each. The machine illustrated weighs 3 tons, and has an output of 160 kilowatts, or 210 horse-power. It may be taken as representative of a large class of alternators in which the axes of the armature coils are radial, thus differing from the disc armatures the axes of whose coils are parallel to the shaft of the machine. There is still another class having ring armatures, the axes of whose coils have a circumferential direction, but our readers will, perhaps, be able to understand their mode of action without further description.

CHAPTER V.

THE THERMAL PRODUCTION OF THE CURRENT.

In our brief summary of the methods available for the production of the electric current, we have pointed out (page 22) that, correlated to the production of heat in a conducting circuit by an electric current passing round it, there is a method of producing an electric current direct from the energy of heat. Strictly speaking, however, the production of heat to which we previously referred as always accompanying the passage of a current through a homogeneous conductor is of a *frictional* nature, and is *irreversible*. In other words, the energy so used up cannot by an inverse process be reconverted into current energy. In this respect the heating effect of the current differs from the chemical and magnetic effects, both of which are under certain circumstances reversible. For instance, the products of the chemical effect can be used, as we have seen, to generate an electric current. Also the magnetic effect is reversible, for the energy used up in creating the magnetic field on the starting of a current is returned to the circuit when the current is broken. It is not so with the heating effect. The energy converted into heat is usually lost or dissipated by radiation, and in the most favourable case can only be utilised as *heat*, the production of which at any particular spot, and in any required quantity, is very completely under control.

Another indication of the irreversible nature of this frictional heating effect is afforded in the fact that the quantity of heat produced in a given conductor by a certain current is *independent of the direction of the current*. A reversal of the direction of the current can be detected by changes in the chemical and magnetic effects, but such reversal makes no change whatever in the heating effect. The quantity of heat produced in the apparatus in Fig. 163 is the same whether the current be passed from left to right or from right to left.

How then are we to convert heat-energy directly into the energy of the electric current? The solution lies in the fact that, although the heating of a *homogeneous* conductor by an electric current is irreversible, there is an additional *reversible heat effect* produced when the conductor is *not homogeneous*. This effect is very much smaller than the other, and was not observed until 1834, although the direct thermal production of the current described on page 247 was discovered in 1822. We shall begin by considering this phenomenon, known from the name of its discoverer as the Peltier effect.

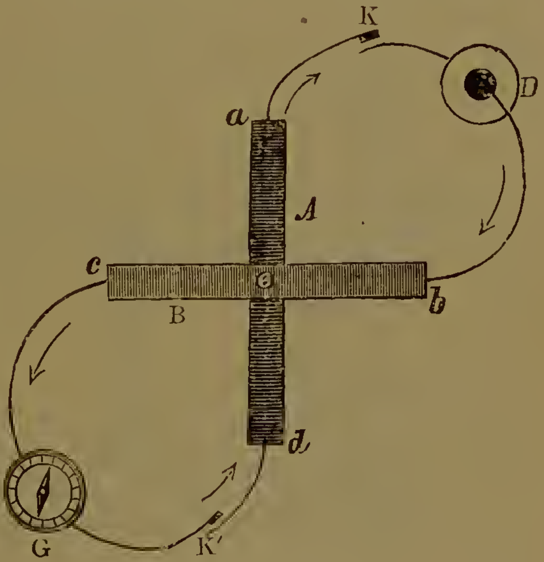

Fig. 136.—Peltier's Cross.

The Peltier Effect is simply this: that whenever an electric current passes from one metal to another, the *junction* is either cooled or heated (apart from the frictional production of heat in the two metals separately) according to the direction in which the current flows. A modification of Peltier's experiment suggested by Lenz shows this cooling effect very forcibly. Two bars A and B (Fig. 136), of antimony and bismuth respectively, are soldered together in the form of a cross; one end *b* of the bismuth bar is joined to the positive pole of a battery D, and one end *a* of the antimony bar is joined through a key K to the negative pole. A small hole *c* is bored at the junction and filled with water. The cross and the water in the hole are reduced to a temperature of 0° C. by being placed in melting snow, and then the key K is closed and the current passed across the junction from bismuth to antimony. Lenz found that in five minutes the water in the hole was frozen and its temperature reduced to 4° C. below the freezing-point.

Peltier himself used at first a differential thermometer, but afterwards demonstrated the existence of the reversible heat effects at the junction by making use of the known facts of thermo-electricity discovered twelve years previously by Seebeck. Before describing Peltier's work further it is necessary to refer to these earlier discoveries.

The Seebeck Effect.—We have already referred to this in our historical summary (page 16). It may be put more briefly thus:—If the junctions of a metallic circuit of at least two dissimilar metals be kept at different temperatures, an electric current will, *in general*, flow round that circuit. Seebeck demonstrated this by placing a bent strip of copper *k* (Fig. 137) on a flat bar of bismuth *a b*. At the centre of the bismuth bar a small magnetic needle *n s* was pivotted, and the apparatus was turned round until this needle, lying in the magnetic meridian, came to rest in a position parallel to the greatest length of the two metals, and within the loop formed by the bi-metallic circuit. On heating one junction *b* of the two metals the needle was deflected in a direction that showed the existence of a current passing through the hot junction from bismuth to copper and from copper to bismuth through the cold junction. If the other junction were heated, the needle was deflected in the opposite direction, showing that the current was reversed in the circuit, but it was still from bismuth to copper through the *hot* junction. In fact, Seebeck showed that the condition for the flow of the current was that above enunciated, namely, that the two *junctions* should be kept at *different temperatures.*

By more extended experiments Seebeck further showed that thermo-electric currents, as they are called, can be

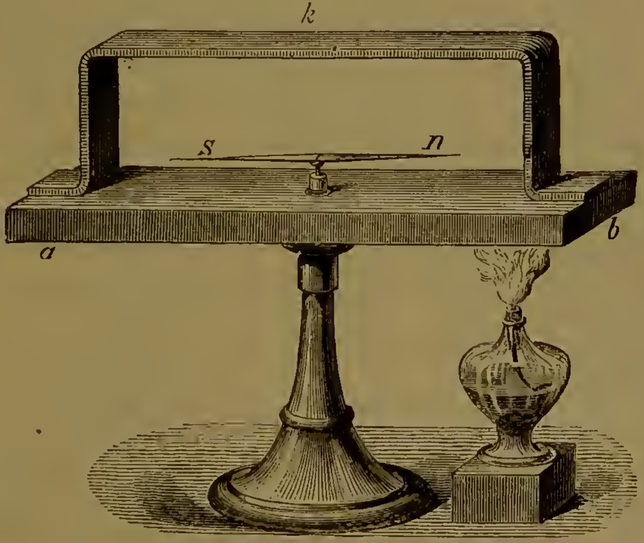

Fig. 137.—Seebeck's Thermo-Electric Experiment.

generated by a combination of almost any two metals or metallic alloys, and he arranged the metals with which he experimented in a thermo-electric order similar to that in which Volta arranged them with respect to the chemical production of the current. In the following table we have arranged some of the more common metals in a thermo-electric series, in such a way that if any two be taken to form part of a circuit and their junction be heated, the current flows from the one highest in the list to the one below it *across the heated junction.* That our readers may have some idea of the very small electric pressures set up in these thermo-electric couples, we have placed in an adjoining column the voltage set up between each metal and lead taken as a standard metal. To produce these tabulated E.M.F.'s, one of the junctions must be kept at the boiling-point of water (100° C.), and the other junction at the freezing-point (0° C.).

TABLE V.—THERMO-ELECTRIC PROPERTIES OF THE METALS.

Metal.	Voltage when paired with Lead between 0° and 100° C.[1]
+ Bismuth	+ ·00682 Volts.
Cobalt	+ ·00320 ,,
Nickel	+ ·00246 ,,
German Silver	+ ·00148 ,,
Platinum (soft)	+ ·00012 ,,
Aluminium	+ ·00006 ,,
Tin	+ ·00001 ,,
Lead	...
Copper	– ·00017 ,,
Platinum (hard)	– ·00022 ,,
Silver	– ·00029 ,,
Gold	– ·00033 ,,
Zinc	– ·00035 ,,
Iron	– ·00149 ,,
– Antimony	– ·00463 ,,

[1] The calculations are based upon Professor Tait's work.

The table can be used to give the voltage when the junctions are at 0° C. and 100° C. of any pair of metals referred to; all that is necessary is to subtract *algebraically* the voltage given for the metal lowest in the table from that which is highest. It is interesting to notice that not only the chemical but the physical state of the material has an effect upon its thermo-electric properties. Thus, soft platinum is positive to hard platinum. For this reason the figures given must be regarded as approximate only even when the metals are chemically pure.

The flow of these currents is, as we have assumed, due to the production of an electric pressure, or E.M.F., in the circuit under the conditions set forth, and if these conditions be fulfilled, the E.M.F. exists whether the currents flow or not, *i.e.*, whether the circuit be complete or not. The magnitude of these thermo-electric E.M.F.'s is very small when compared with those of a simple galvanic cell. The values are given in the above table as fractions of a volt with respect to lead as a standard metal, and with a difference of temperature of 100° C. between the junctions. It will be remembered that the volt is rather less than the E.M.F of a Daniell's cell. The E.M.F. in any case is, with certain exceptions, nearly proportional to the difference of temperature. The metals are marked positive and negative with regard to lead in the same way that they are regarded as + and – in a galvanic cell. Thus bismuth causes a current to pass through the *hot* junction, the principal seat of the E.M.F., towards lead just as the current flows from zinc to copper in a battery. Bismuth is, therefore, thermo-electrically positive to lead.

Since the difference of temperature of the junctions determines the direction and magnitude of the current, the existence of the current will, *vice versâ*, demonstrate a difference of temperature at the junctions. It was in this way that Peltier demonstrated the reversible heating and cooling effect at the junction.

A B (Fig. 138) is a bi-metallic bar of antimony and bismuth, the end A being antimony and the end B bismuth; the ends of this bar are joined to the central cups of the simple mercury commutator C. The two far cups of the commutator are joined to the battery E, and the two near cups to the galvanometer G. By throwing over the movable switch the bar can be placed either in circuit with the battery or in circuit with the galvanometer. If the bar be placed first in circuit with the galvanometer, no current is indicated, all parts of the circuit being at the same temperature. Let the switch be now thrown over and the current from the battery be sent through the bar from bismuth to antimony for a few minutes. On throwing back the switch the galvanometer will be deflected by a current flowing through the bar from antimony to bismuth, which shows that the junction of these two metals has been *cooled* by the battery current. If the connections with the battery be reversed and the battery current be sent through the bar from antimony to bismuth, the galvanometer on being placed in circuit will show that the junction was heated by the battery current.

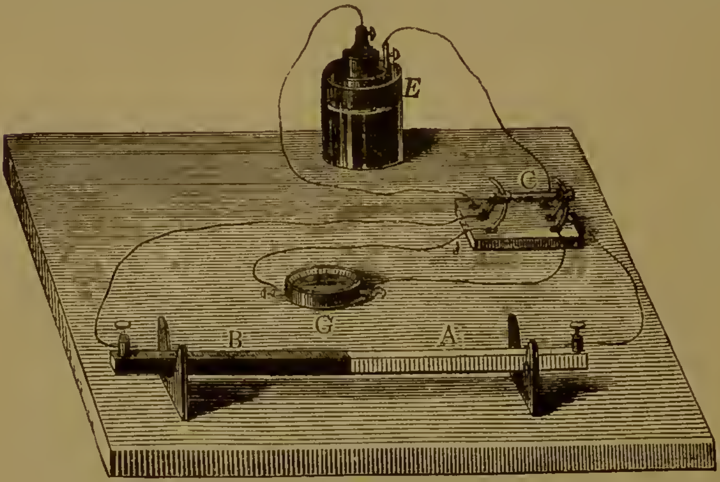

Fig. 138.—Peltier's Bar.

Fig. 136 shows how the Peltier cross may be used to exhibit the same result. When the battery current is passed through the junction *e* from bismuth to antimony by closing the key K, we have seen that the junction is cooled. If the battery current be broken at K and the key K′ closed so as to complete the galvanometer circuit, a current will be found to flow from antimony to bismuth across *e*; these two currents are indicated by the arrows.

We can now see whence the energy of the thermo-electric current is derived. If the bismuth-antimony junction in a closed metallic circuit be heated, a current flows across the junction from bismuth to antimony; but such a current, as Peltier showed, cools the junction, or in other words *absorbs heat-energy* at the junction. The junction is colder than it would be if the current did not flow, and it is the heat-energy which thus disappears that is converted directly into the energy of the electric current.

Thermo-Electric Inversion.—In 1823 Cumming discovered a new thermo-electric fact. Working with a copper-iron couple and with a galvanometer in circuit, he kept one junction at a constant *low* temperature and gradually heated the other. As the latter temperature rose he observed that the current after a time rose less rapidly than the temperature, that at 275° C. it ceased to rise altogether, and that if the hot junction was heated beyond this point the current diminished until it fell to zero, although the temperatures of the two junctions were widely different. Heating the hot junction still further, Cumming found that the direction of the current was actually *reversed*.

Subsequent experiments have given a very simple explanation of these phenomena. On examination it has been found that there is no Peltier effect at a copper-iron junction when it is at 275° C.; that *below* this temperature there is the usual Peltier effect, and copper is thermo-electrically *positive* to iron; and that *above*, the Peltier effect is the other way, and the relative positions of the two metals are reversed. The temperature of 275° C. is, therefore, called the *neutral* temperature for copper and iron, and it can be shown that if one junction be below this temperature and the other above, the direction of the current depends upon which junction is most distant from the neutral temperature. If the cold junction is most distant, the current is in the usual way (as shown in the table) but if the hot junction is furthest from the neutral point, the current is reversed.

This strange behaviour of copper and iron is, moreover, only part of the more general case, for most pairs of metals have *a* neutral temperature exhibiting the same properties, though in many cases it is either too high or too low for ordinary experiment.

The Thomson Effect.—In an unequally heated metallic circuit there is still another reversible heat effect, much smaller in amount than the Peltier effects at the junctions. Its existence was theoretically predicted and experimentally demonstrated by Lord Kelvin (then Sir William Thomson), who showed that the passage of a current from the cold to the hot part of an unequally heated copper conductor cooled the conductor, and that its passage in the opposite direction heated the conductor. These reversible effects must not be confounded with the irreversible and usually much greater frictional heating which always accompanies the current, for they are superposed upon this latter, causing it to be a little less in the first case and a little greater in the second. In iron the effect is of the opposite kind, the passage from hot to cold cooling iron and from cold to hot heating it.

The experiments so far considered relate to thermoelectric effects in, and at the junction of, *metals*, but the Seebeck and Peltier effects have also been observed at the junctions of metals and electrolytes, and at the junctions of two electrolytes. To consider these fully would lead us too far afield, but as an indication of the magnitude of the phenomena, we may mention that two plates of amalgamated zinc dipping in zinc sulphate solution develop a thermoelectric pressure of 710-millionths of a volt per 1° C. difference of temperatures.

Thermopiles.

In order to increase the very small E.M.F.'s given in the table on page 248, two methods may be employed. First, the temperature differences of the hot and cold junctions may be increased, for the E M.F.'s in the table are those due to a temperature difference of 100° C. only. This is done when it is desired to use the arrangement as a current generator, but a limit is soon reached to the possible temperature of the hot junction, which at the outside must not be raised beyond the fusing-point of the more fusible of the two metals.

Another method is to treat the thermo-electric junctions as cells are treated when high E.M.F.'s are required, that is, to put them "in series" with one another. This is especially useful when it is desired to use the phenomena to detect small changes in temperature. The method will be understood by an inspection of Fig. 139, which shows six bars of two metals, say antimony and bismuth, arranged in this way as a thermo-electric battery. Now the current flows from bismuth to antimony across the hot junction, and therefore, since the metals occur alternately in the circuit, it is obvious that only *alternate junctions* must be exposed to the source of heat, for if all the junctions were heated, their E.M.F.'s would oppose one another. Thus, if the junctions 1, 3 and 5 are heated, an E.M.F. will be set up at each of them tending to drive electricity from bismuth to antimony across the junction; but all these E.M.F.'s act in

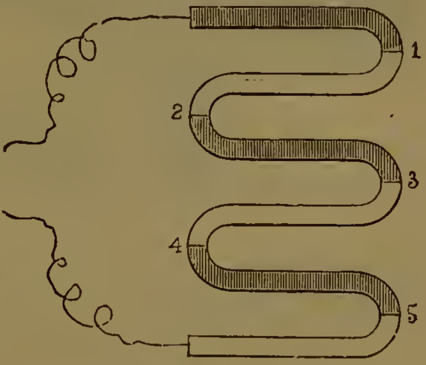

Fig. 139.—Thermo-Electric Battery.

the same direction round the circuit, and their effects are therefore added together in that circuit. The junctions 2 and 4 and the left-hand ends of the extreme bars are, of course, to be kept cold.

A series of junctions similar to those in Fig. 139 may obviously be placed on top of one another with insulating material between, and the electrical connections so made that all the E.M.F.'s at the hot junctions are added together. In this way thermopiles, such as that shown in Fig. 140, are built up into a convenient form for the particular experiment for which they are designed. The one in Fig. 140 is of the pattern used by Melloni in his researches on radiant heat. On the left-hand side of the pile 20 bi-metallic junctions are exposed, but thermopiles have been built containing 100, 150, or more junctions in a small space. The terminals *x* and *y* are in connection with the two ends of the pile, and when joined to a suitable and delicate galvanometer, the combination forms a most valuable arrangement for the detection of minute differences of temperature. The complete thermopile as used by Melloni is shown in Fig 141. One end is furnished with a cone *C* to converge the radiant waves on to one face of the pile, and the opposite face is screened from outside disturbances by a little shutter. The arrows show the direction of the current

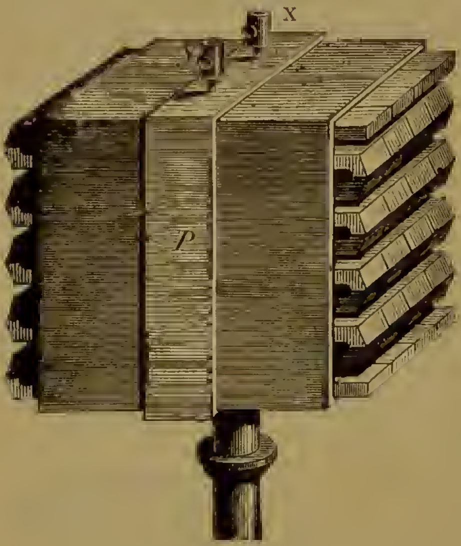

Fig. 140.—The Thermopile.

when the right-hand face is warmed. With this instrument Melloni was able to detect differences of temperature no greater than the $\frac{1}{5000}$ part of a degree.

THERMOPILE-GALVANOMETERS.

The extraordinary delicacy of Melloni's thermopile, combined with a suitable galvanometer for detecting small differences of temperature, soon led experimenters to attempt the solution of the problem of still further increasing the delicacy.

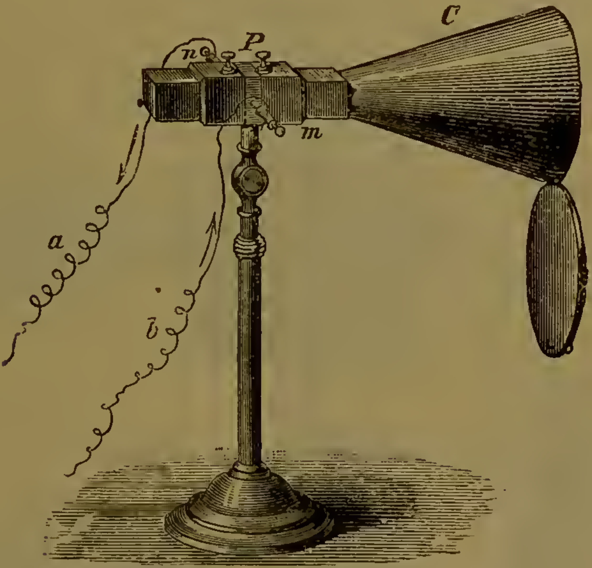

Fig. 141.—Melloni's Thermopile.

One suggestion which seemed to promise success was to do away with the outside galvanometer and make one instrument of the thermopile and the galvanometer, thus producing a *thermopile-galvanometer.* The earliest worker in this direction was Sturgeon, who in 1836 constructed instruments capable of indicating very small differences of temperature. We shall refer to his work presently.

Professor Forbes in 1886[1] constructed the thermopile galvanometer, shown in Fig. 142. B and A are two wedge-shaped blocks of bismuth and antimony soldered together, and at the thin end of the wedge a hole is bored through the junction equally out of each metal. On the thin side of the hole the metals are filed away quite thin, and the outside face is blackened at the junction so as to absorb

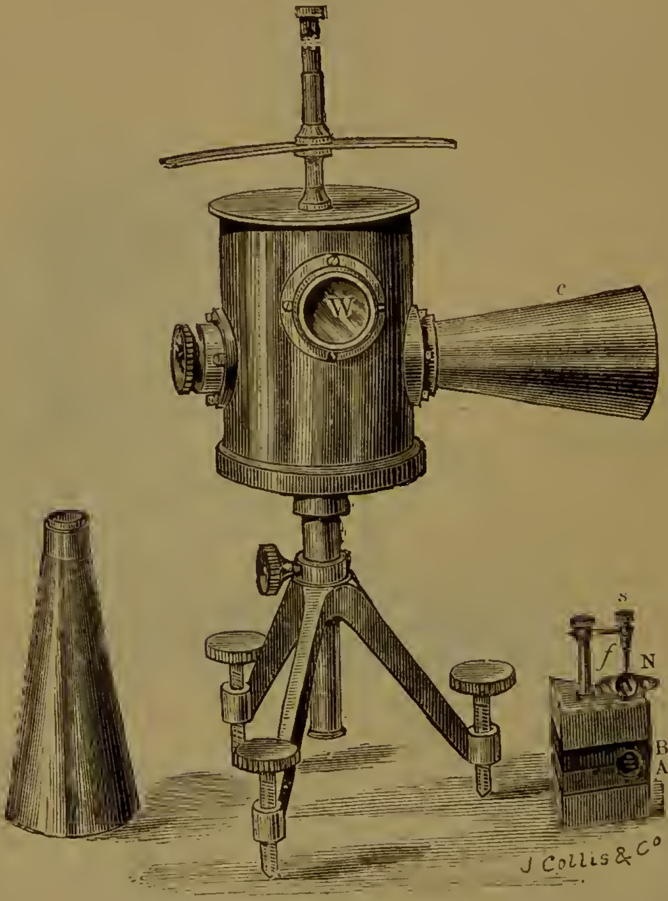

Fig. 142.—Forbes' Thermopile Galvanometer.

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[1] *Proceedings of the Royal Society*, 1886.

radiant energy the more readily. If this face on the right-hand side in the figure be slightly warmed, a current will be set up which will flow down from the bismuth to the antimony on the right, pass along the lower block, up through the thick junction on the left, and complete its circuit in the bismuth. Now, although the E.M.F. at the junction is very small, yet the current developed may be quite a large one—as we shall see in the next chapter—because of the extremely small resistance of the circuit. This current circulates round the hole in the block, and in this hole, therefore, a magnetic field is set up, which will affect a delicately suspended magnetic needle placed in it. A system of three small needles is suspended there by means of a wire passing through a small vertical hole in the upper block. At the top of this wire there is a little mirror and damping vane N, and the whole is hung from the support S by means of a fine silk fibre *f*. This is then placed in the case with the mirror opposite the window W, and the thin junction opposite the cone C. The radiations are directed on to the junction by this cone, currents are set up in the coil, and the movements of the needle and mirror are observed by means of one of the devices described in detail on page 347. These movements have a definite relation to the difference of temperatures of the thin and the thick junctions, and can be employed to measure the difference. With this arrangement, the presence of a candle-flame can be readily detected at a distance of some yards.

The Radio-Micrometer.

But Professor Boys has since constructed a far more sensitive instrument, which he calls the *radio-micrometer*, because of its power of detecting the presence of excessively minute quantities of radiant energy.

In all galvanometers for measuring the electric current the effect is produced, as we shall show in detail in a subsequent chapter,[1] by the interaction of two magnetic fields, one at least of which is due to the current to be measured. One of these fields is free to move, and the current is measured either by the actual motion, or in some dependent way which we need not now consider. In a beautiful series of instruments, of which M. D'Arsonval's galvanometer (Fig. 181) may be taken as a type, the current is sent round a conducting loop suspended by a wire in a strong magnetic field. When the current passes through it, the loop tends to set its plane at right angles to the field, but in doing so twists the suspending wire, and the angle through which it actually moves measures the strength of the current.

Now it is obvious that if the whole thermo-electric circuit be suspended in this way in a powerful magnetic field, its resistance can be made very small, so that even a very minute electromotive force at one of the junctions may cause a sufficient current to deflect the circuit through a sensible angle. Moreover, since the current is generated in the suspended coil itself, we may use something far more delicate than a metallic conducting wire for the suspension, and thus still further increase the sensitiveness of the apparatus.

The first to employ this method was Sturgeon, who in 1836[2] suspended little thermo-electric circuits in front of the poles of a magnet. M. D'Arsonval and Professor Boys, both quite independently, re-invented the method in 1886 and 1887 respectively. The latter, on having his attention called to Sturgeon's work, constructed an instrument according to the description given by Sturgeon, and found it to be "capable of showing very small effects of heat."

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[1] Part II., Chapter IX., pp. 335 to 383.

[2] *Scientific Researches*, by William Sturgeon.

The principle of the radio-micrometer will be understood from an inspection of Fig. 143,[1] which represents the suspended circuit of one of the early forms. Two small sheets of antimony, *Sb*, and bismuth, *Bi*, are cut to the shape shown, and soldered together along the vertical junction. The upper corners remote from the junction are connected by a rectangle of thin copper wire. This is then suspended by the rod *a*, and a delicate fibre not shown in the figure, between the poles, *N S*, of a powerful permanent magnet, and to further intensify the field a block of soft iron is fixed in the space surrounded by the rectangular loop. A little light mirror is attached to *a*, and the movements of the rectangle are observed by methods which will be described in detail later.[2] If now radiant energy be directed on to the line between *Sb* and *Bi*, whilst the remoter junctions are screened, a current will flow from *Bi* to *Sb* across this junction, and complete its circuit through the copper rectangle. The suspended loop will tend to turn in the magnetic field, but this tendency will be resisted by the torsion of the suspending fibre. The

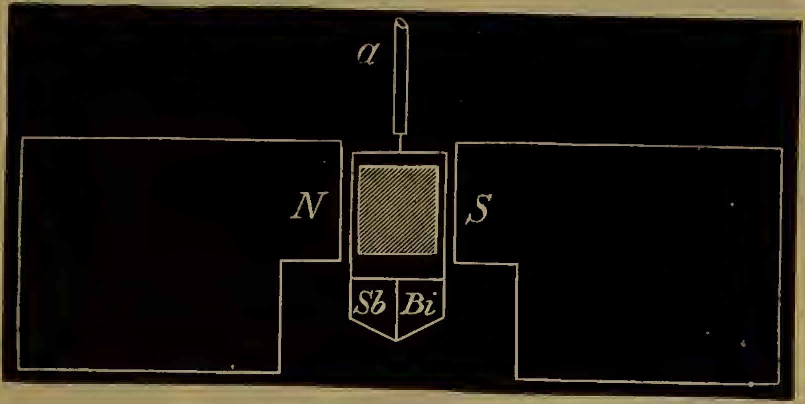

Fig. 143.—Early form of the Radio-Micrometer.

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[1] *Philosophical Transactions*, 1889 A.

[2] *See* pp. 346 to 349.

actual motion will depend upon the current strength, and, since the circuit resistance is constant, upon the E.M.F. at the junction; therefore, finally it will bear some proportion to the amount of radiant energy directed upon the junction, and can be made to measure that energy.

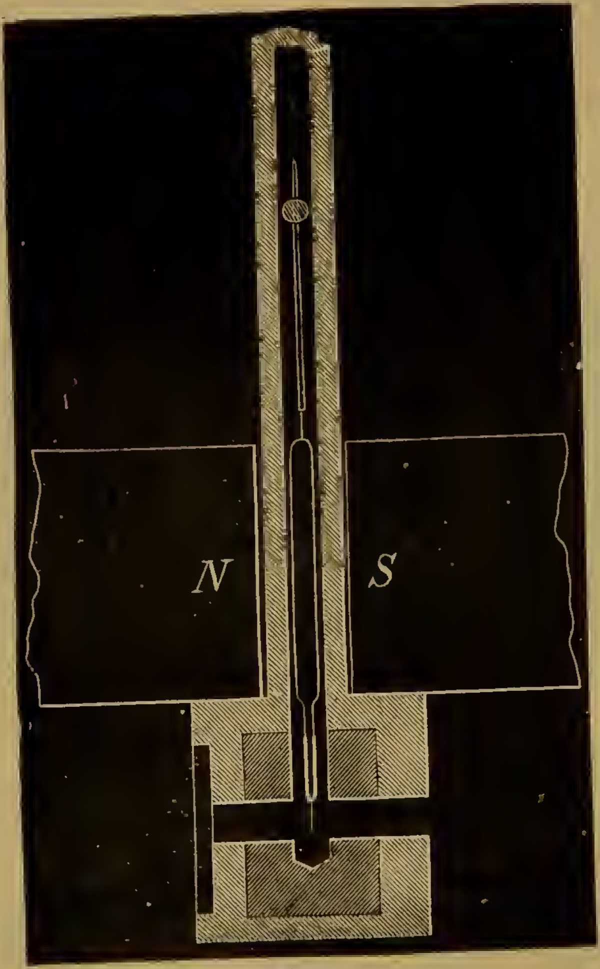

Fig. 144.
The Radio-Micrometer.

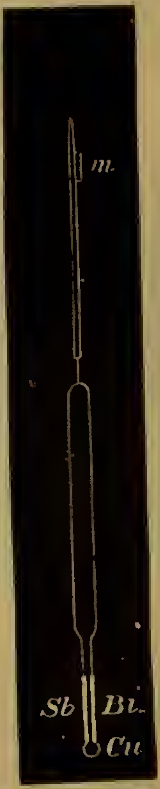

Fig. 145.

Not content with the performances of this delicate instrument, Professor Boys entered into an elaborate mathematical calculation with the object of determining the best proportions for the various parts. The result was the production of the instrument represented in Figs. 144 and 145. Two small bars, *Sb* and *Bi*, of certain alloys of antimony and bismuth, which were found to be more suitable than the pure metals, are soldered at their lower ends to a small disc *Cu* of copper foil. These bars measure $\frac{1}{3} \times \frac{1}{50} \times \frac{1}{200}$ inch, and are, therefore, very small; the copper disc is only $\frac{1}{10}$ inch in diameter. The upper ends of *Sb* and *Bi* are soldered to a very fine piece of copper wire, bent into the form of a little circuit 1 inch long and about $\frac{1}{10}$ inch wide. This is fastened to a connecting stem, to which is attached a little mirror *m*, $\frac{1}{10}$ inch square, and $\frac{1}{200}$ inch thick. The whole is suspended by a single quartz fibre 4 inches long and $\frac{1}{6000}$ inch in diameter. It may be mentioned incidentally that it was during the evolution of this instrument that Professor Boys investigated the properties of these excessively fine quartz fibres, and invented his ingenious method of making them. The whole suspended arrangement now described is placed in a brass tube as shown in Fig. 144, and fixed so that the copper wire circuit lies between the poles, N S, of a powerful magnet. And here an interesting detail occurs. Bismuth and antimony have both sufficiently strong magnetic properties to destroy the usefulness of such a delicate instrument if the bars *Sb* and *Bi* were placed in a strong magnetic field. It is therefore necessary to *screen* them magnetically, and this is done by placing them in the midst of a block of iron, which is shown by darker shading in Fig. 144. The lines of force from N to S, which would otherwise have passed through the space occupied by the thermo-electric bars, run through the iron by preference, and thus leave this space clear and free from magnetic lines.

The radiations are directed on to the thin disc of copper foil through the narrow hole in the lower block of metal. So thin and light is this foil that very little heat suffices to change its temperature, and the smallest change of temperature at once sets up an electric pressure at the *Sb*, *Bi* junctions, attached to it. This causes a current in the circuit, which therefore rotates in the magnetic field until pulled up by the torsion of the quartz fibre.

The instrument is extraordinarily sensitive. It is calculated that a readable deflection can be obtained by a rise of temperature of the copper foil not greater than one-millionth of a degree, and experiment shows that a movement can be obtained by directing on to the foil a quantity of heat no greater than would be radiated on to a halfpenny by a candle-flame 1,530 feet away from it. Still further sensitiveness has been more recently attained, and Professor Boys states that he can now detect the radiations from a candle at a distance of two miles.

COMMERCIAL THERMOPILES.

The problem of utilising thermopiles for the production of the currents required in the various applications of electricity has always attracted a great deal of attention, since by their means we directly convert heat-energy, which is readily procurable, into the energy of electric currents. Also, since the path of the current through the thermopile lies through metals or alloys which are good conductors, the internal resistance of the arrangement can be made very small. On the other hand, the greatest drawback is the smallness of the E.M.F.'s produced at each junction with any practicable temperature, thus necessitating the employment of a great number of "couples" if an E.M.F. of useful magnitude is to be produced. Also the fact that the materials of the thermopile are not only good conductors of electricity, but also of heat, militates against its success. For the effects sought depend on the *difference* of temperature between the hot and the cold junctions, and this difference the good thermal conductivity of the materials tends to remove. Then, again, the Peltier effects at the two junctions tend to equalise their temperatures, for this effect cools the hot and warms the cold junction. But perhaps the greatest practical difficulty is due to the unequal coefficients of expansion of the materials employed. As a thermopile in intermittent use is being continually cooled and heated, these inequalities of expansion and contraction tend to rack it to pieces. Indeed, it is probable that a single heating and cooling leads to more wear and tear than would result from a long-continued use of the pile with its best working current flowing.

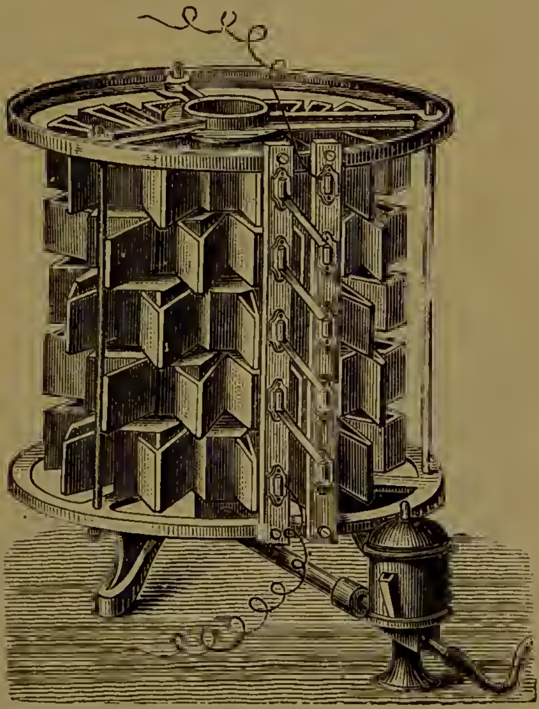

Fig. 146.—Clamond's Thermopile.

These being the chief difficulties, which up to the present have not been very successfully overcome, we shall content ourselves by describing two modern forms of thermopiles, which may be taken as types of the best that have been produced.

One of the well-known thermopiles of Clamond is shown in Fig. 146. It consists of fifty pairs of elements, and is arranged so that the heat can be obtained by burning coal gas. The pairs of elements are arranged above one another in five tiers, insulated from one another, and each containing ten pairs, the arrangement of each tier being as depicted in Fig. 147. Each pair of elements consists of a piece of sheet-iron, F, of the shape shown, and a comparatively massive block, A, made of an alloy consisting of two parts of antimony and one part of zinc. The successive junctions are alternately in the central cylindrical space, S, and on the outside of the pile. They are numbered consecutively in

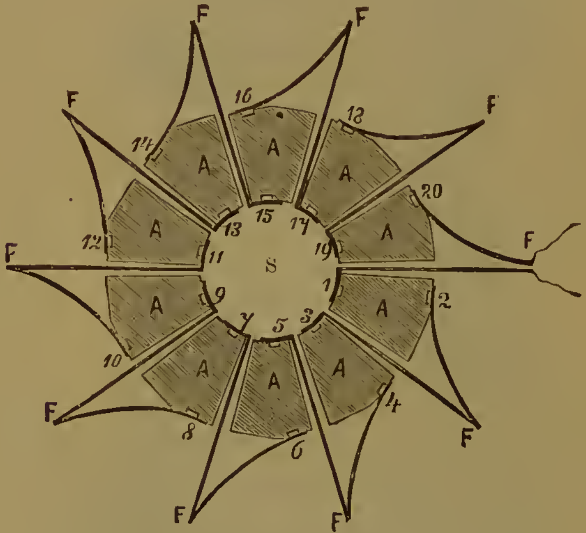

Fig. 147.—Sectional Plan of Clamond's Thermopile.

the direction in which the current tends to flow when the inner junctions are heated, and thus the path of the current through the pile can easily be traced. The peculiar projecting shape given to the sheet-iron is for the purpose of exposing a large surface to the cooling action of the outside air in order to assist in keeping the external junctions cool.

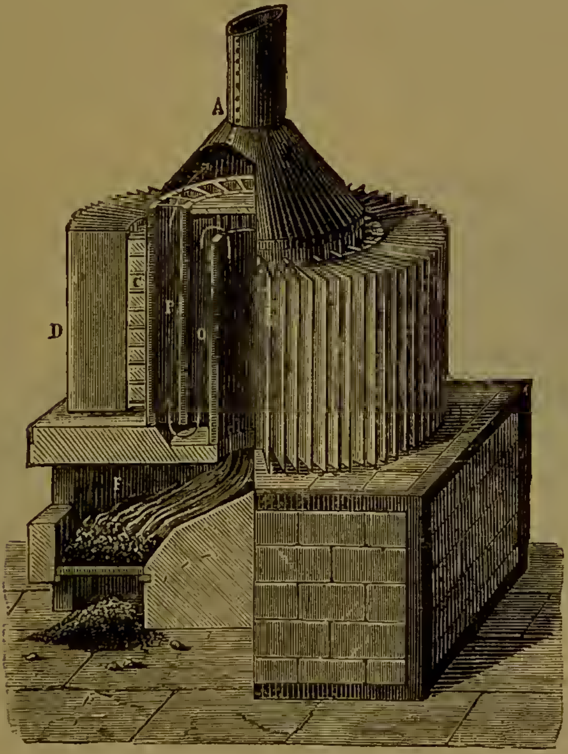

Fig. 148.—Improved Clamond Thermopile.

In some large thermopiles sheets of copper projecting outwards are attached to the cold junctions for the purpose of more freely radiating the heat which is generated in these by the Peltier effect, and that also which reaches them by conduction from the hot junctions. These copper radiators thus play an important part in the action of the apparatus.

After the various tiers are built up over one another, a tubular gas-burner, of porcelain with little holes opposite each inner junction, is fixed in the central space. From these holes small gas flames play upon the junctions, which are, however, protected from the direct action of the flames by asbestos cement. Under these circumstances, each thermo-electric couple develops an E.M.F. of about one-thirtieth of a volt, and the whole E.M.F. of the fifty pairs is about 1·8 volts, the consumption of gas being six cubic feet per hour.

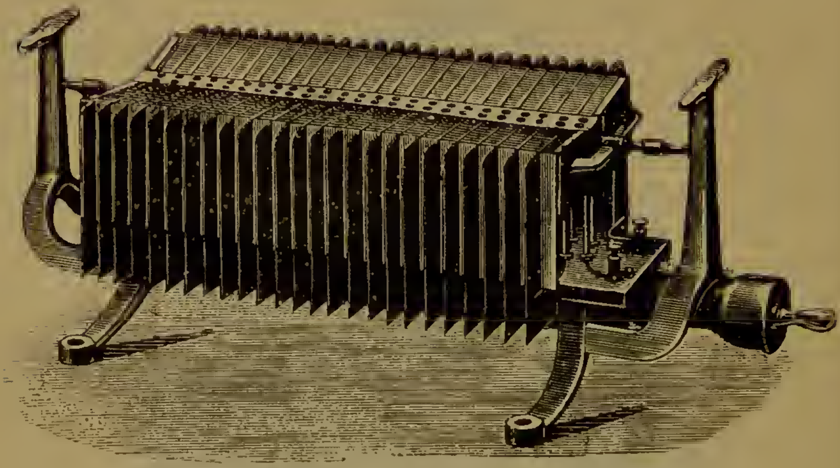

Fig. 149.—The Gülcher Thermopile.

In 1879 Du Moncel constructed the much larger Clamond Pile shown in Fig. 148. This pile was heated by a coke furnace, the hot gases from which passed to the chimney A, through the cylindric flues as shown by the arrows. The couples C are arranged round the outside of the annular cylindric space P. Copper radiators D are attached to the outer junctions, but are, of course, electrically insulated from them. The pile consists of two separate batteries of 3,000 couples, each divided into 30 sets of 100 couples. Each battery has a total E.M.F. of 109 volts, and an internal resistance of 15·5 ohms, and the two together consume 22lb. of coke per hour.

The Gülcher thermopile shown in Fig. 149 was exhibited at the Frankfort Exhibition of 1891. It consists of fifty thermo-electric couples, the electro-positive element of each pair being a tube of nickel. Fifty of these nickel tubes are arranged in two rows down the centre of the pile; they are, of course, insulated from one another, and each tube surrounds the flame of a small one-hole soapstone gas-burner. The negative elements consist of rectangular blocks of an alloy of antimony having a high melting-point. There are twenty-five of these blocks on either side, and each block is connected to one of the nickel tubes by a nickel connecting piece. The various couples are insulated from one another by sheets of asbestos, and the necessary electric connections are made by copper sheets, which, projecting outwards, also serve as radiators.

One of these piles burning 6·7 cubic feet of gas per hour has an E.M.F. of 3·8 volts, and when giving a current of 4·63 ampères has an external potential difference of 1·9 volts, thus giving a useful output of 8·8 watts. In order to compare this result with a gas engine and dynamo, we may take the useful output of four such piles, burning 26·8 cubic feet per hour, as 35·2 watts. But the useful output of a small gas engine and dynamo burning the same quantity of gas would not be less that 650 watts, or about 18½ times that of the four thermopiles. Herr Gülcher claims that this thermopile is the most economical yet produced, and these figures will therefore enable the reader to compare the relative values of the mechanical and thermal methods of producing electrical current energy from the same source, namely, coal-gas.

Quite recently a thermo-electric stove has been devised for household use. The stove is of an ordinary type, and its primary object is for heating purposes, but a thermopile is arranged in connection with it in such a way that the *waste* heat of the stove is utilised to generate an electric current, which is said to develop a useful power of 30 to 40 watts. As this power is obtained from heat which would otherwise be wasted, the device may lead to some useful practical result.

Part II.

LAWS OF THE ELECTRIC CURRENT.

CHAPTER VI.

LAW OF CONDUCTION.

In the preceding section we have described in detail the various methods by which the electric current can be produced or generated, and incidentally we have, from time to time, referred to the laws which regulate the flow of the current or govern the phenomena which, either invariably, or under certain circumstances, accompany it. The quantitative statement of these laws has been avoided, except so far as was absolutely necessary to elucidate important points connected with the methods of generation. But these methods having, we hope, been now made clear to our readers, it will be most interesting to turn to the quantitative aspect of the laws referred to. This will not be found to demand any concentrated effort, for the fundamental laws are grand in their simplicity, and it is with these only that we propose to deal. The consideration of them naturally leads to a description of the numerous beautiful measuring instruments which are used in electric-current work, and to this description we shall devote a special chapter.

After explaining the law of conduction, we shall deal with the three characteristic effects of the current, then with measuring instruments, and lastly, as being more conveniently dealt with in one place, the modifications introduced, and the aspect of the laws when the currents are either fluctuating or alternating.

When in the light of modern science we look back upon the simplicity of the law involved, it is almost incredible that many years should have elapsed between Volta's discovery of the chemical method of producing a steady flow of electricity in a conducting circuit, and the enunciation of the conditions governing that flow. But, as in several other cases of great discoveries, the simplicity of the generalisation is, perhaps, the best measure of its grandeur. For, on the one hand, the law is so simple, that, like the law of gravitation, the least instructed can grasp its significance and value, and yet, on the other hand, like the same law, the full explanation of it still offers some of the grandest problems to the consideration of the searcher after truth. To the genius of G. S. Ohm, of Munich, we owe the clear enunciation of the law which he gave to the world in 1827, in a pamphlet entitled, "Die Galvanische Kette Mathematisch Bearbeitet." From the name of its discoverer it is known as Ohm's law, and is one of the most far-reaching and important laws in the whole realm of physics.

Ohm's Law.—Stated in its baldest form, this celebrated law asserts that the ratio of the electric pressure in any part of a conducting circuit to the electric current that it produces in that part of the circuit is always the same, no matter how great or how small the pressure and current may be. Thus, if a potential difference (or electric pressure) of one-millionth of a volt between the two ends of a certain wire produces a certain current in that wire, then a potential difference of one volt will produce a current exactly one million times as great, and any other pressure will produce its corresponding current. On the other hand, if we change the wire for a longer or a thicker one, or one made of a different material, we find that the potential difference of one volt produces a different current to what it did in the former wire, but that, again, in the new wire the current produced is strictly proportional to the potential difference; if we double the one we double the other, and so on. The particular ratio between the potential difference and the current it produces in a given conductor is thus evidently a distinct property of the conductor, just as much as its colour, density, hardness, or any of the other distinguishing properties that belong to it. It is, therefore, fitting that this additional property should receive a special name, and it is now universally known as the **electrical resistance** of the conductor. Thus, by the term electrical resistance of any conductor, we mean neither more nor less than *the ratio between any potential difference to which its two ends may be brought and the electric current thereby produced.* The definition assumes that there is no source of electric pressure (or E.M.F.) in the conductor itself; if there is, it must be allowed for in reckoning the pressure available for driving the current.

The term resistance adopted for the above ratio is justified by the well-ascertained fact that the energy converted into heat by the flow of the current is directly proportional to the numerical value of the ratio. The generation of this heat may very well be regarded as due to a kind of *electric friction* which *resists* the flow of the current, giving rise, just as in the case of mechanical friction, to the production of heat. As a rule, this heat is wasted and is a source of loss; but sometimes, as shown in a subsequent section, part of it may be usefully employed.

The law just enunciated, which governs the flow of the electric current in conductors, is very analogous to the law which governs the flow of incompressible liquids, such as water in pipes. In order to produce a *steady* flow of water in a pipe, a steady difference of hydraulic pressure must be maintained at the two ends, and the current will then flow from the end where the pressure is higher to that at which it is lower. Moreover, a certain difference of pressure will always produce a certain rate of flow of water, provided the pipe be not changed in any way. Any change in the length or diameter of the pipe will affect the rate of flow. Again, any increase or decrease of the driving pressure (or pressure-difference) will lead to a corresponding increase or decrease in the rate of flow, though for extreme pressures the law of proportionality of pressure to flow is not so strict as in the electric case. Lastly, the flow of the water in the pipe leads to the conversion of energy into heat, due to the *frictional resistance* to the flow; this heat, even more frequently than in the electric case, cannot be applied to any useful purpose, and the energy that it represents is wasted.

Returning to the electrical phenomena, there is a further limitation involved in our definition of resistance to which we must briefly allude, and that is, that the passage of the current is not to alter the physical condition of the conductor in any way; for the electrical resistance, like many of its other properties, depends on this condition. Thus, the density, hardness, and oftentimes the colour, of a body are changed when its temperature is changed, and so likewise is its electrical resistance. For small changes of temperature the change in the resistance is so small in many materials as to be negligible, but if the current is large enough to raise the temperature of the conductor considerably, then with the change of temperature there is a change of resistance, or, in other words, the ratio of potential difference to current changes. For example, in the case of a glow-lamp, when the current necessary to raise it to incandescence is passed through the filament, the glowing filament has an electrical resistance very different from that of the black carbon filament in the cold lamp.

Resistance being thus a physical property of every conductor, and its magnitude depending only on the material, size and shape of the conductor, the selection of a standard, or unit of resistance, could be made quite arbitrarily, by taking any convenient conductor, of a certain size and shape, and measuring all other resistances in terms of its resistance. This would be analogous to the method of measuring the specific gravities of bodies in terms of the density of water as unity, or the length of a piece of cloth in terms of the standard yard, which is merely the length of a certain bar of metal preserved in Westminster Palace, and from which copies are taken for use. In the early days of the development of electrical science, and especially of telegraphy, this method was followed, and each experimenter who aimed at expressing his resistances quantitatively, arbitrarily adopted the unit most convenient to himself, which was frequently the resistance of a certain length of a certain piece of wire which he had in his laboratory. It was thus well-nigh impossible to compare the results of one experimenter with those of another, for though the material of the standard conductor was carefully specified, the influence of small changes in the composition of the material, and especially of certain impurities, was not accurately known. A great step in advance was made when Siemens, in 1860, introduced his mercury unit and measured all his resistances in terms of the resistance of a column of *pure* mercury, one metre long and one square millimetre in cross-section, at the temperature of melting ice (0° C.). The great advantage of this unit is that the material employed is one which can readily be obtained in a state of purity, and that, being a liquid, at 0°C. it has a definite physical constitution. Still, the **Siemens unit**, as it is called, is an *arbitrary* unit, and in its choice no account was taken of the other units, especially the mechanical ones, which are frequently met with in electrical measurements.

We have seen that to maintain an electric current in a conductor, work has to be done and energy used up somewhere. Also that part, if not all, of the energy so used up reappears as heat-energy in the conductor, and that the heat-energy thus produced is directly proportional to the resistance of the conductor. But heat-energy, as energy, can be expressed in terms of the ordinary mechanical units of work, that is as *foot-lbs.* in ordinary British units of work, or as *ergs* in the C.G.S. (centimetre, gramme, second), or metric system of units. Now, it will obviously conduce to simplicity in the calculations, if the unit of resistance be so chosen as to have some simple relation to the mechanical units which have been already fixed by other considerations. For instance, the simplest relation of all would be that in which the *unit of resistance* was *such that one erg of heat energy was produced in it by unit current flowing for one second*, the unit of current having already been decided upon. This unit is usually referred to as the *absolute unit of resistance.*

In 1861 the British Association appointed a strong committee to investigate the question of electrical units, and to determine what units would be most convenient for practical and scientific use. The committee decided that the best practical unit of resistance would be that which was *one thousand million times* (*i.e.*, 10^9) the above absolute unit of resistance. This practical unit was called the **Ohm**, in honour of G. S. Ohm, the discoverer of the fundamental law that regulates the flow of the current through conductors. The necessity for taking such a large multiple of the absolute unit for the practical unit arises, first, from the smallness of the erg as a unit of energy, and secondly, from the necessity for expressing resistances in ordinary use with a small number of digits. Thus, a mile of ordinary telegraph wire has a resistance of about 13 ohms, but expressed in absolute units this resistance would be 13,000,000,000, a number much too awkward for every-day use. Even then, however, the magnitude fixed upon is only a compromise, for the *range* of resistances with which the electrician has to deal is enormous. Thus, in measuring the resistance of short thick pieces of good conductors the ohm is far too large a unit, and he expresses his results in terms of the **microhm** (or *little* ohm), which is *one-millionth* part of the ohm. Again, in measuring insulation resistances the ohm is much too small, and he uses instead the **megohm** (or *great* ohm), which is *one million times* the ohm.

But now a practical consideration forces itself upon our notice. It is all very well to define the *ohm* as one thousand million times the absolute unit of resistance, but for actual use one must have a concrete standard to refer to. The case is analogous to that which occurs in connection with the *metre* as a unit of length. Originally the metre was defined as the one-ten-millionth part of the distance from the earth's equator to either of its poles. Now, it is obvious that such a definition is of no value for practical use, because when, for instance, a merchant wishes to measure the length of a piece of cloth, it is quite out of the question that he should trouble himself with difficult and laborious measurements connected with the size of the earth. Therefore, as a result of careful terrestrial measurements, a platinum bar was constructed, to represent as accurately as possible the required fraction of the earth's circumference, and copies of this bar are made for ordinary use in every-day life. By comparison with these, any particular length can be easily measured. So for the ohm, the practical unit of resistance. The determination of the resistance of any conductor directly in absolute units is even more laborious than the terrestrial measurements just referred to, but the comparison of one resistance with another is an easy and simple operation. Therefore, when the more difficult measurement has been made, the results are embodied in actual standards for reference. Such a standard is the *standard ohm.*

There still remains the question of defining the practical ohm, apart from its connection with the absolute unit. Without going into the pros and cons of the matter—for this would lead us too far afield—we may state briefly that the *form* of the Siemens mercury unit has distinct advantages over its competitors for this purpose. The only thing to be altered is the length, which very numerous experiments have shown must be 106·3 centimetres instead of 100 centimetres (*i.e.*, one metre). Also, as it is much easier to *weigh* a fine column of mercury than to determine its cross-section accurately, it has been found best to specify the weight which corresponds to a uniform cross-section of one square millimetre. Thus we arrive at the following definition:—"*The* **ohm** *is the resistance of a column of pure mercury of uniform cross-section* 106·3 *centimetres long at* 0°C *and weighing* 14·4521 *grammes.*

Such is the definition; but, just as with the standard metre bar, the actual defined standard is seldom used, but copies of convenient form, and made of other materials, are employed. One of these, recommended by Dr. Fleming, is shown in Fig. 150. A coil of silk-covered platinum silver wire is contained inside the flat ring C, and its two ends are soldered to the thick copper rods A B, A′ B′, which pass up through the brass tubes T T′, without touching them. Besides being covered with silk, the coil is embedded in paraffin wax; D is a block of ebonite which mechanically

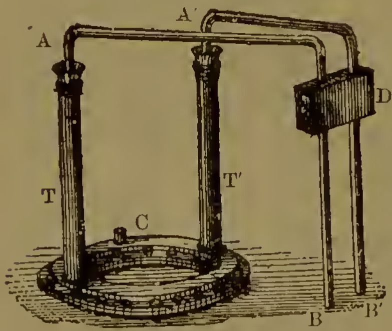

Fig. 150.—Standard Resistance Coil.

supports the copper rods. When used, the ring C is placed in a vessel of melting ice to bring it to the temperature of 0°C., the temperature at which its resistance is accurately known, and the ends B B′ are inserted in cups of mercury which are connected to the other parts of the circuit.

But in measuring lengths we not only want our standard metre or standard yard, as the case may be, but we also require long tape or chain measures for long lengths, and small carefully divided scales for fine work. So, in measurements of resistance, we need many different resistances of known value. These are usually made up in resistance boxes, as they are called, and consist of various lengths of wire of various thicknesses. Each wire is coiled, as seen in Fig. 151, and its two ends connected to two adjacent blocks of brass on the top of the box. Thus, the ends of the coil W^1 are connected to the blocks C^1 and C^2, and those of the coil W^2 to the blocks C^2 and C^3. If we suppose that one pole of the battery is connected through a conductor to the block C^1, and the other pole to the block C^3, the current can only get from C^1 to C^2 by passing through the coil W^1, whose resistance is marked on the top of the box; this coil, therefore, forms part of the circuit. The plugs P^1 and P^2 consist of short conical pieces of brass with ebonite tops; they are carefully turned, so as to accurately fit the holes between the brass block C^1, C^2, C^3. When the plug is inserted in any hole it forms an easy

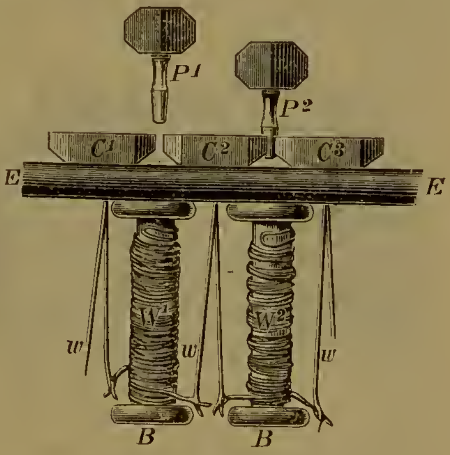

Fig. 151.—Ordinary Resistance Coils.

conducting path for the current from one block to the other. In the figure the current can pass far more easily from C^2 to C^3, through the plug P^2, than through the coil W^2, and therefore practically none of it passes through W^2, which is thus out of circuit. In other words, the coil W^2 is *short-circuited* by the plug P^2. By inserting and withdrawing the plugs the resistance of the circuit can thus be quickly altered without interfering with the permanent connections. Fig. 152 shows how a box of eleven coils is arranged; T^1 and T^2 are the terminals to which the two ends of the rest of the circuit are firmly joined, and then any resistance or combination of resistances within the range of the box can be added to this circuit by withdrawing the proper plugs. Other devices, such as sliding connections of various kinds, are sometimes used for altering the resistances of a circuit, but the blocks and plugs just described are by far the most reliable. It should be noticed that in Fig. 151 the wire is coiled double, being bent back on itself at its middle point, as shown at the top of the bobbins. This is to diminish the magnetic effect of the coil as much as possible, for when a current passes it circulates in one-half of the wire in a clockwise direction, and in the other half in a counter-clockwise direction. The magnetic effects of the two halves therefore oppose one another, and by careful winding the resultant effect may be very nearly zero.

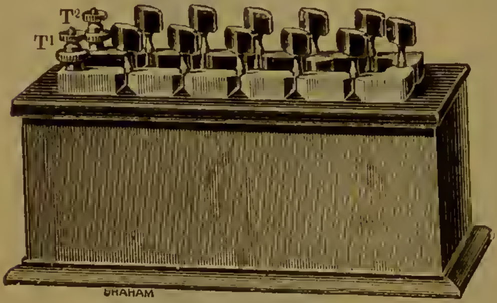

Fig. 152.—Resistance Box.

Measurement of Resistance.—A reference to page 271 will suggest that the method of measuring resistance most in accordance with the definition is to measure simultaneously the potential-difference and also the current flowing; the ratio of these two quantities will be the resistance of the conductor. If the potential-differences and currents are measured in absolute units, the ratio will give the resistances in the absolute units already referred to. More particularly if the potential-differences be measured in *volts* and the currents in *ampères* the resulting ratios will be the resistances in *ohms*. Before considering the method of determining potential-differences and currents, it will be simpler to refer briefly to the chief method of determining a resistance by comparison with a known resistance. Most of the accurate determinations are made by such comparisons.

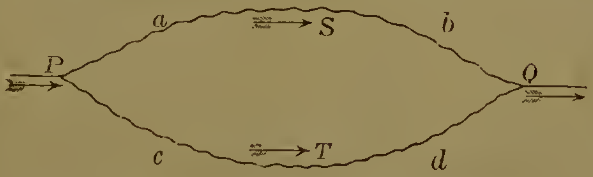

Fig. 153.—Principle of Wheatstone's Bridge.

Comparison of Resistances.—The most sensitive method of comparing the relative values of two resistances was devised by Christie and introduced by Wheatstone; with its various modifications it is known as *Wheatstone's Bridge*. Fig. 153 represents diagrammatically the principle of the test. P and Q are two points in a circuit which are connected by two sets of conductors, P S Q and P T Q; in passing from P to Q the current passes through both conductors in proportions, according to Ohm's law, inversely as their resistances; for the potentials at P and Q, and the potential-difference between them, are the same for both conductors. The potentials of the various points along the conductor, P S Q, must, therefore, diminish as we pass from P to Q, and Ohm's law tells us that the fall of potential must be proportional to the resistance passed. A similar rule holds for P T Q. If now we select a point, S on P S Q, it is evident that there must be *some* point on P T Q which is at the same potential as S. On joining these points across by a conductor no current will flow along this conductor, because its two ends are at the *same* potential, and if the conductor be the wire of a galvanometer the index of the instrument will remain stationary. But the potential-differences on the two sides of S are in the ratio of the two resistances *a* and *b* on these two sides; similarly the potential-differences on the two sides of T are in the ratio of the resistances *c* and *d*. If, therefore, S and T are at the *same* potential, when tested by the galvanometer, the above two ratios must be equal, and we have—

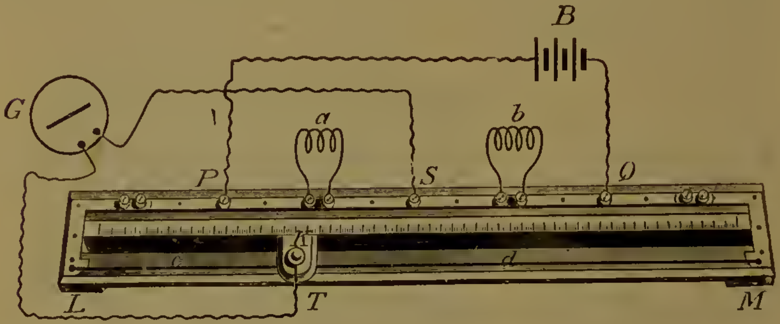

Fig. 154.—The Metre Bridge.

$$\frac{a}{b} = \frac{c}{d}$$

Let a be an unknown resistance, then, if we know the value of the ratio $\frac{c}{d}$ and also the value of the resistance b, we can easily calculate the value of a.

The simplest apparatus for carrying out the test in practice is that shown on Fig. 154, and is usually known as the "Metre Bridge." For corresponding electrical positions the same letters are used as in Fig. 153. *B* is the battery from which the current is led to the point *P*, and after dividing between the conductors, *Pa Sb Q* and *Pc Td Q*, passes to *Q* and back to the battery. *a* is the unknown resistance to be measured and *b* is a known resistance, both inserted in the branch, *P S Q*. The resistance of the branch *P T Q* is almost entirely that of the uniform stretched wire *L T M*. The galvanometer *G* has one terminal connected to *S* and the other to a sliding key *K*, which is to be moved along the wire *L M* until the galvanometer shows no current; when this is the case we have

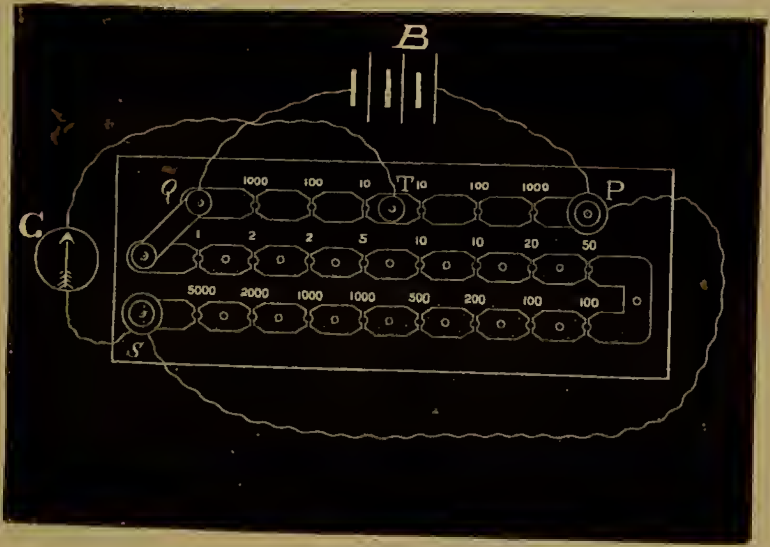

Fig. 155.—Diagram of Connections of Ordinary Wheatstone Bridge.

found the point, *T*, which is at the same potential as *S*. Since *L T M* is a uniform wire the ratio of the resistance *c* and *d* is the same as the ratio of the lengths *L T* and *T M* of the wire; these lengths can be read off on the scale in the middle of the board. If now we multiply the known resistance *b* by the ratio of *c* to *d* (or of *L T* to *T M*), we have the required value of the resistance *a*. The wire *L M* is usually (but not necessarily) a "metre" long, hence the name given to this form of Wheatstone's Bridge.

Although the Metre Bridge is the simplest application of the principle of Wheatstone's Bridge, it is somewhat clumsy for ordinary use, because of the long length of stretched wire. Numerous other modifications have, therefore, been devised, and the one most largely used is shown diagrammatically, with battery and galvanometer joined up, in Fig. 155, whilst Fig. 156 shows the box of test-coils in perspective. In both figures the same letters are used for corresponding points as in Fig. 153. The practical differences between this form and the wire form are two: first, the ratio of *c* to *d* is that of the resistances of coils of known value; and secondly, balance, as it is called, is finally obtained by altering the value of the known resistance, *b*. This alteration is effected by inserting one or more coils in the arm S Q, by means of the plugs as already explained. The resistance to be measured is placed between P and S, and the value of the ratio of *c* to *d* can be altered by using different coils in the arms P T and T Q. In actual practice press keys are inserted both in the battery branch P B Q and in the galvanometer branch S G T.

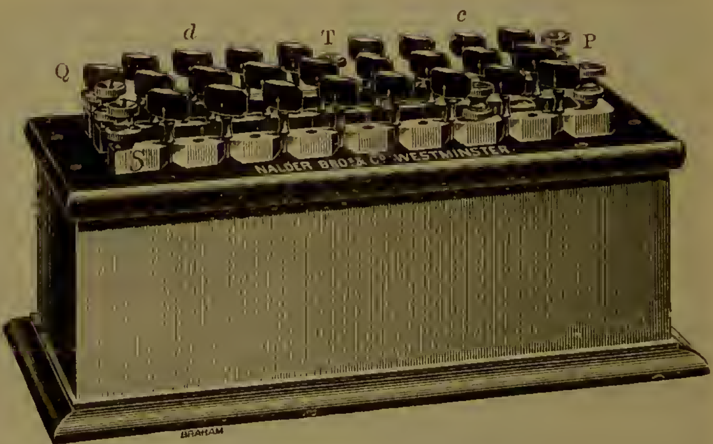

Fig. 156.—Ordinary Wheatstone Bridge; Coils only.

Another method of comparing the resistances of two conductors consists in observing the potential-differences required to send the same current through each. Very high resistances can also be measured by observing the rate at which they discharge a pair of charged conductors. For details of these and other methods we must refer the reader to books on electrical testing.

Liquid Resistances.—The methods of measuring and comparing resistances that we have just described are applicable to liquids as well as solids, but the application is complicated by the chemical effect always produced when the current passes from a liquid to a solid, or *vice versa*. We have seen (page 44) that this chemical effect appears electrically as an opposing E.M.F., which cuts down the total available pressure, and therefore cuts down the current. Now an *increase of resistance* would also cut down the current. If, therefore, the chemical effect be overlooked or neglected in measuring the resistance of a liquid, the resistance will appear to be greater than it really is. The consideration of the methods of eliminating or of counterbalancing the chemical effects are too technical to describe here, and we merely refer to the matter to caution our readers against attempting to measure liquid resistances without taking proper account of these effects. Details of how this may be done will be found in books on electrical testing.

Values of Resistances.—We shall now give a few figures relating to the actual value of the resistances of various materials, which we hope may guard our readers against making very serious mistakes. As already remarked, the range of values is enormous, and hence arises the danger of mistakes of a magnitude which would be impossible in the every-day concerns of life. In tabulating the actual resistances of various materials any convenient size and shape may be taken as the standard size and shape whose resistance is specified in the table. For scientific purposes the most convenient standard of this kind is a prismatic piece of the material one centimetre long and one square centimetre in cross-sectional area. For telegraphic purposes other standard sizes are found more convenient. For our purpose we prefer to adopt a standard size, which we hope will be thoroughly familiar to our readers; and, therefore, in the following table the resistances are those of cylindric conductors, each one yard long and one-tenth of an inch in diameter. The resistances of the materials that are most commonly used in electrical work are given in ohms, or fractions of an ohm, for pieces of this size and shape. When not otherwise specified, the temperature is 0° C.

TABLE VI.—RESISTANCES OF VARIOUS MATERIALS.

Material.	Resistance of one yard length one-tenth inch in diameter at 0° C.	Resistances relatively to Silver.
Silver (annealed)	·0027 ohm	1·
Copper (hard drawn) ...	·0029 ,,	1·07
Gold (hard drawn) ...	·0038 ,,	1·4
Zinc...	·0101 ,,	3·7
Platinum	·0162 ,,	6·0
Iron (annealed)	·0174 ,,	6·4
Tin	·0237 ,,	8·8
Lead	·0351 ,,	13·0
German Silver	·0374 ,,	13·9
Platinoid	·0812 ,,	30·
Mercury	·1700 ,,	63·0
Carbon (electric light) ...	7 to 15 ohms	2,600 to 5,500
,, (graphite)... ...	4·3 to 76 ,,	1.520 to 2,800
Water with 35 per cent. of Sulphuric Acid	22,390 ,,	8·2 millions
Sulphate of Copper ...	105,500 ,,	38·6 ,,
Sulphate of Zinc	121.300 ,,	44·9 ,,
Pure Water at 18° C ..	6,787 million ohms	2·5 billions
Glass (Bohemian) at 60° C.	109.000 billion ,,	40·4 trillions
Gutta Percha at 24° C. ...	812,000 ,, ,,	300·7 ,,
Glass (Flint) at 60° C. ...	1·8 trillion ,,	667· ,,
Ebonite at 46° C.	505 ,, ,,	187·000 ,,
Dry air	Practically infinite	—

It has been already remarked that the differences in the electrical resistance of various materials are enormous, and an inspection of this table will fully justify this remark. Indeed, the numbers in the lower part of the table are so great, compared with those in the upper, that it is quite impossible for the mind to grasp any real idea of the ratio. Take copper and gutta-percha for instance. A yard of the former, one-tenth of an inch in diameter, has a resistance of not quite three-thousandths of an ohm, whilst the resistance of a piece of the latter of the same size is nearly one trillion ohms. Or we may express the relation in another way, by saying that a copper wire of the same resistance and cross-section as the yard of gutta-percha would have a length 1,675 million times the mean distance from the earth to the sun, or a length along which it would take light 27,000 years to travel.

On the other hand, the range of resistance amongst the metals is expressed by comparatively small numbers. Thus, mercury, the metal of highest resistance that we have included in the table, has only sixty-three times the resistance of silver. But many liquids, which are usually regarded as good conductors, have a very much higher resistance than any of the metals specified. Thus, the resistance of dilute sulphuric acid is several millions of times that of copper, and more than one hundred thousand times that of mercury.

The rules for calculating the resistance of any conductor of uniform-cross section from the values given in the table are exceedingly simple. Both experiment and theory show that the resistance of any conductor is directly proportional to its length and inversely proportional to its sectional area. Put into symbols this rule may be written—

$$R = \rho \frac{l}{A}$$

where l is the length, A the area of cross section of the conductor, and ρ is a constant depending upon the material and the units employed. If the length be measured in yards and the cross-sectional area in terms of the area of a circle one-tenth of an inch in diameter, ρ has the value given in the preceding table. In scientific work more congruent units are used, and, as a rule, l is measured in centimetres and A in square centimetres. The value of ρ for any material when these units are employed is usually called its *specific resistance.*

Returning to our table, if it is required to find the resistance of a metallic wire of any length and having a diameter of one-tenth of an inch, all that is required is to *multiply* the number given in the table by the *length* of the wire expressed *in yards.* Thus, the resistance of a copper wire of this diameter and having a length of 1,000 yards would be 2·9 ohms. On the other hand, in dealing with wires of different thicknesses we must remember that the cross-sectional area varies as the square of the diameter, and, therefore, to find the resistance of a round wire a yard long and of any other diameter, we must *divide* the resistance in the table by the *square of the diameter* expressed in *tenths of an inch.* Thus, a copper wire one yard long and $\frac{1}{1000}$th of an inch in diameter would have a resistance of 29 ohms (*i.e.*, $\cdot 0029 \div (\frac{1}{100})^2$). Resistance may, therefore, be increased either by increasing the length or diminishing the diameter of a conductor, but a relative change in the latter is much more important than a corresponding change in the former.

Combinations of Resistances.—Frequently, especially in the use of the electric light, it is necessary to connect several resistances together so as to conform most readily to the conditions under which current can be supplied to them. It is, therefore, useful to have a general idea of the effect on the total resistance of the various combinations that may be employed. There are in general use two principal methods of connecting conductors which are to be supplied with current from the same source; these are known as (*a*) connections for *series working*, and (*b*) connections for *parallel or multiple working*.

In *series working* the conductors are placed one after the other in the circuit, and the *same current* flows through all. Thus the end of conductor A (Fig. 157) is joined to the beginning of conductor B, and the other end of conductor B to the beginning of conductor C, and so on; finally the beginning x of the first conductor and the end y of the last one are joined to the source of supply. By Ohm's law the resistance of any conductor is the ratio of the potential difference to the current. Now a little consideration will show that the potential difference of x and y must be the *sum* of the potential differences at the ends of the separate conductors A, B, C, &c., and it is evident that the *same current* passes through all the conductors. Therefore, the resistance of the compound conductor lying between x and y is the *sum* of the resistances of the separate conductors A, B, C, &c. Thus we have the rule:—*The total resistance of any number of conductors in* SERIES *is the* SUM *of the resistances of the separate conductors.*

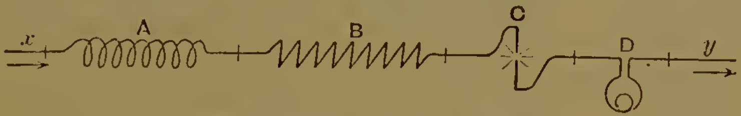

Fig. 157.—Conductors in Series.

In *parallel or multiple working* each of the conductors used forms a separate path for the current between the two points which are connected to the source of supply. The system is shown in Fig. 158, where P S and Q T are two thick conductors or "leads" of inappreciable resistance, one of which, P S, is joined to the positive pole of the source of supply, and the other, Q T, to the negative pole. These "leads" may be regarded as representing the supply mains which are now put down in all important towns for the public supply of electric energy. The "leads" are connected by the various conductors A, B, C, . . ., of the system, and these conductors are then said to be arranged "in parallel." Through each of them there is a conducting path from P to Q, so that if one or more of them be removed the current can still flow through the remaining ones. This system, besides being used by supply companies, is also usually employed inside the houses in domestic lighting with "glow" lamps, as any number of lamps in various parts of the house can be turned on or off without stopping the current through the other lamps. In this case P S and Q T must be taken to represent the two wires coming into the house from the street "supply" mains.

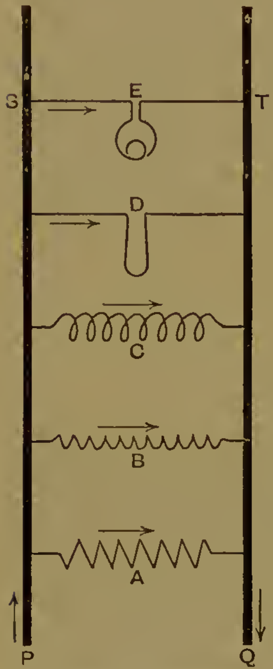

Fig. 158.—Conductors in Parallel.

In calculating the total resistance between P and Q, we must remember that the *addition* of each new conductor, however high its individual resistance may be, offers a new path for the current, and, therefore, *diminishes the total resistance.* It is, therefore, simpler to deal with *conductivities* rather than resistances. The conductivity of a conductor is the *reciprocal* of its resistance, and may, therefore, be defined as *the ratio of the electric current to the potential difference that produces it.* Thus, if a conductor have a resistance of 5 ohms, its conductivity is $\frac{1}{5}$; if its resistance be $\frac{1}{100}$th of an ohm, its conductivity is 100, and so on. No name has yet been adopted for the unit of conductivity, though Lord Kelvin has suggested the word

MHO (*i.e.*, ohm spelt backwards). Now the total current passing from P to Q is evidently the sum of the separate currents along the various branches A, B, C, . . . and the potential difference driving this total current is the same as that which drives each separate current; namely, the potential difference between P and Q. As, therefore, the total conductivity is by definition the ratio of the total current to the potential difference, we see that the *total conductivity between two points joined by several conductors in parallel is equal to the sum of the conductivities of the separate conductors.*

To express this law in symbols, suppose R is the total *resistance* from P to Q, then $\frac{1}{R}$ is the *conductivity*; and if $a, b, c, \ldots$, be the resistances of the separate conductors, the above law leads to the equation :—

$$\frac{1}{R} = \frac{1}{a} + \frac{1}{b} + \frac{1}{c} + \frac{1}{d} + \cdots\cdots$$

there being as many terms on the right-hand side as there are separate conductors.

Other systems are in use known as *series parallel* systems, in which the conductors are partly in series and partly in parallel, but the principles and rules already given can be applied to the modifications, the necessary changes being obvious. Some of these combined systems will be referred to in detail in connection with the methods adopted for the public supply of electric energy.

Arrangements of Batteries.—Some of our readers may from time to time be tempted to make experiments with electric currents, using ordinary primary batteries as current generators. It may not, therefore, be without interest if we point out how the preceding laws of conduction influence the amount of current that can be sent through a given external circuit with a certain maximum number of cells available for the purpose. Or, to put it otherwise, we may show how to arrange the cells so as to produce the greatest possible current in the given circuit.

The rules which we have just given for the combinations of resistances can also be applied to batteries, for the latter are also conductors having resistance. There is one important change, however, namely, that these new conductors are seats of E.M.F., and that, therefore, the two ends (*i.e.*, the positive and negative terminals of the cells) have opposite electrical properties. This difference must not be lost sight of, but bearing it in mind we may state generally that cells may be joined up to form a battery either (*a*) in series, or (*b*) in parallel, or (*c*) in any combination of series and parallel.

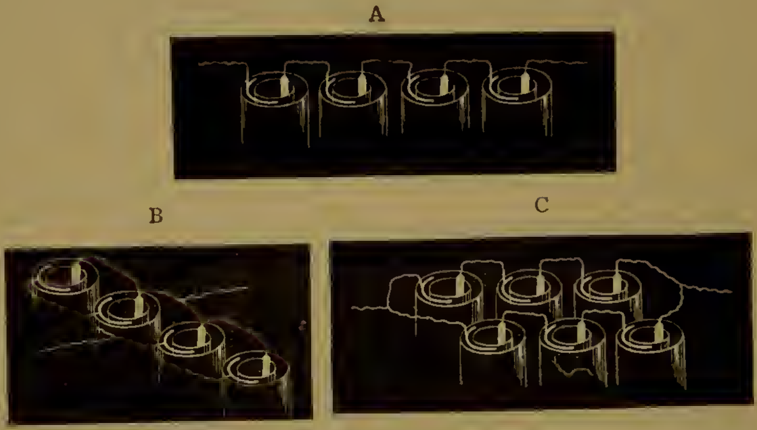

Fig. 159.—Arrangements of Cells to form Batteries.

The methods of doing this may be made clear by an inspection of Fig 159. A represents a battery of four cells joined up in "series," that is, the negative terminal of one cell is joined to the positive terminal of the next, the negative of this second cell to the positive of the next, and so on. The terminals of the completed battery are the positive terminal of the first cell and the negative terminal of the last.

In B we have represented the method of joining up the four cells in "parallel." Here *all the positive* terminals are joined together by wires, and a point on any of these wires may be taken as the positive terminal of the completed battery. Similarly *all the negative* terminals are joined together by another set of wires, any point of which may be taken as the negative terminal of the battery.

Lastly, in C we have a representation of six cells joined up partly in series and partly in parallel. In this arrangement the cells are first divided into two groups of three each, the cells in each group being joined up in series similarly to A, as already explained. The positive terminals of the two groups are then joined together, and form the positive terminal of the complete battery, and the negative terminals are joined to form the negative terminal of the battery. The cells are then said to be joined up "three in series and two parallel." The six cells might also have been joined up "two in series and three parallel," and with a greater number of cells other arrangements would be possible. One precaution only is necessary, and that is that the number of cells in each "series" row should be the same throughout the battery.

For brevity in drawing diagrams there is a conventional method of representing cells and batteries, which is depicted in Fig. 160 for the above three groups, A, B, and C, of Fig. 159. This consists in representing a single cell by two lines, one long and thin and the other short and thick. The first of these, the long thin line, is taken to represent the plate in connection with the positive terminal, whilst the short thick line represents the plate connected to the negative terminal. A comparison of Figs. 160 and 159 will show that, adopting this convention, the corresponding parts of the two figures represent the same grouping of cells. It may be remarked that, in accordance with the convention, the current in each case shown in Fig. 160 will flow through an external circuit from the wire on the left-hand side to the wire on the right-hand side.

But how do these different arrangements affect the current in an external circuit? This current we know is given by the ratio of the total *effective* electromotive force to the total resistance. The total resistance in any given case is made up of two principal parts, namely, the resistance of the external circuit and the internal resistance of the battery. With the former we are not concerned, for it is supposed to be fixed by considerations other than those we are now dealing with. But, from what we have just said about combinations of resistances, it is obvious that the internal resistance of the battery depends upon the grouping of the component cells. If these cells are in "series," then the internal resistance, according to the rule given, is equal to the sum of the resistances of the separate cells. But if the cells are in "parallel" and of uniformly equal resistance, the rule for a parallel combination shows that the internal resistance of the battery is equal to the resistance of a single cell *divided* by the *number* of cells. Lastly, if the cells are partly in series and partly in parallel, the internal resistance is found by dividing the resistance of a single row of cells by the

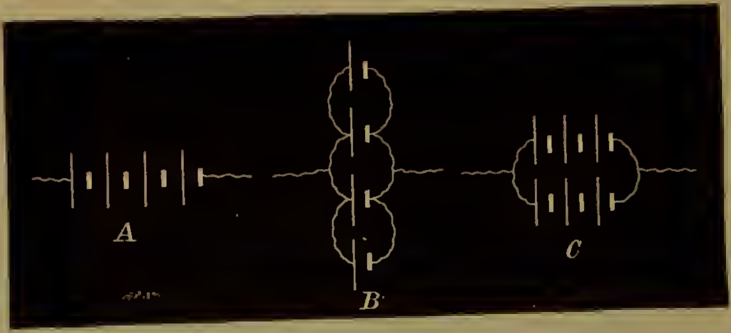

Fig. 160.—Conventional Representation of Batteries.

number of rows in parallel. Did we then only consider the resistance of the battery, we should always join the cells in parallel, as this would give us the least resistance for the complete circuit, and, therefore, *cœteris paribus*, the greatest current.

But the current depends not only on resistance, but also, and directly, upon the *effective* electromotive force. Now it is easy to show that this effective E.M.F. depends on the arrangement of the cells. Take first the "series" arrangement. We have seen (page 42) that the electric potential of the positive terminal of a cell is always higher than that of the negative, so that when the two are joined by a wire an electric current flows from the first to the second. Now in a series arrangement (A, Fig. 160) the potential of the positive terminal of the first cell is higher than that of its negative terminal. But the latter is electrically the positive terminal of the second cell, and has the same potential as this positive terminal, which in its turn has a higher potential than the negative of No. 2 cell. Therefore, the potential difference (P.D.) of the positive of No. 1 and the negative of No. 2 is equal to the *sum* of the P.D.'s of the terminals of No. 1 and No. 2 taken separately. Proceeding in the same way, it can be shown that the P.D. of the positive terminal of the first cell and the negative of the last, in a series arrangement, is the sum of the P.D.'s of all the cells joined up. The same reasoning that applies to P.D.'s can be used for E.M.F.'s, and, therefore, the effective E.M.F. of a row of cells in series is equal to the sum of the separate E.M.F.'s of each cell. Thus, although the joining up of cells in series increases the internal resistance of the battery, it also increases the effective E.M.F., and, therefore, in certain circumstances may be advantageous.

Consider now the effect of a "parallel" grouping on the effective E.M.F. In B, Fig. 160, all the positive terminals are metallically joined together, and are therefore all at the same potential; similarly, all the negative terminals are at the same potential. Thus, the potential difference between the positive and negative terminals can only be that of a single cell, and the same may be said of the effective E.M.F. Therefore, the joining of cells in "parallel," although it reduces the internal resistance, gives us a combination which has only the *effective* E.M.F. of a single cell, and so far as E.M.F. is concerned is not as advantageous as a "series" grouping.

Lastly, in a combination of series and parallel a little consideration will show that the effective E.M.F. is that of one of the series rows taken by itself. Thus, in C, Fig. 160, the effective E.M.F. of the six cells is only the sum of the separate E.M.F.'s of three cells.

Since then "parallel" grouping, or an approach to parallel grouping, not only diminishes the resistance, but also the effective E.M.F., how can we decide what grouping to adopt in any given case? Fortunately, the rule is a very simple one, although we cannot give here the mathematical proof of it. It is this:—So group the cells that *the* **internal** *resistance is as nearly as possible equal to the* **external** *resistance.* In practice this rule leads to the conclusion that when the external resistance is very high the cells should be joined in series, when it is very low they should be joined in parallel, and when it is intermediate a calculation should be made in accordance with the rule to find out what grouping is best. When this rule is followed, there is obtained through the given external circuit the *maximum* current which the cells available will furnish.

Loss of Pressure inside a Current Generator.—In the foregoing we have inferred that there is a distinction between the electromotive force (E.M.F.) of a battery and the potential difference (P.D.) of its terminals. We wish now to point out briefly how the distinction arises. In

Chapter III. of Part I. we have shown that the E.M.F. of a cell depends on the chemical properties of its various component parts. This E.M.F. is the total effective pressure available for driving a current round any circuit of which the cell forms a part. But the cell itself is formed of conductors through which the current must necessarily flow, and which like all other conductors possess definite electrical resistances. The driving of the current through these resistances, therefore, uses up some of the total electric pressure, and the actual loss so caused can be calculated, by Ohm's law, as the product of the current into the resistance. The pressure available for driving the current round the external part of the circuit is, therefore, less than the E.M.F. by these "lost volts," as they may be called, and it is to this *available pressure* that the *term P.D* is applied. A little consideration will show that if the E.M.F. be constant the P.D. depends on the current and the internal resistance, and if the latter be also constant the P.D. falls as the current rises. Put into mathematical shape the relation is expressed by the simple equation—

$$V = E - b C$$

where E and V are respectively the E.M.F. and the P.D., C is the current and b is the internal resistance of the battery. If the current be zero, that is if the battery be an open circuit, the potential difference of the terminals is equal to the electromotive force, but whenever the battery is generating a current the P.D. falls short of the E.M.F. by the number of volts obtained by multiplying the current by the internal resistance.

The above remarks apply to all current generators, whether they be batteries, dynamos, or thermopiles. These all have *some* internal resistance, and the available P.D. is always less than the full E.M.F. set up, by an amount equal to the product of the current into this internal resistance.

CHAPTER VII.

LAWS OF CHEMICAL AND THERMAL ACTION.

THE law which regulates the flow of a steady current in a conductor having been explained, we turn next to the laws governing those effects by which the presence of such a current is recognised, and in the present chapter shall consider from this point of view the chemical and thermal effects.

1. Laws of Chemical Action.

The "chemical" effect or action of the electric current has been frequently referred to and discussed in the preceding pages; and now, after dwelling more in detail on the fundamental phenomena, the beautifully simple quantitative laws which underlie that action will be considered. On page 18 we have described the chemical effect manifested when an electric current traverses a conductor in these words:—"*If the conductor be a liquid which is a chemical compound of a certain class called ELECTROLYTES, the liquid will be decomposed at the places where the current enters and leaves it.*"

In this brief description two or three points should be carefully noted. First of all, the *conductor* is to be a *liquid.* So far experiment has not discovered any indication of the chemical action of the current in solid conductors. Secondly, the *liquid* must be a *conductor.* A reference to the values of the resistances of liquids on page 284 will show that some liquids are for all practical purposes non-conductors or insulators. Amongst the most common we may cite petroleum, turpentine, most mineral oils and *pure* water; in these no chemical effect is observed, probably because even with large potential differences the current which passes is infinitesimal. Again, the *liquid conductor* is to be a *chemical compound.* This condition excludes from the list all liquid conductors that are elements, more especially mercury and molten metals, and the further condition that it is to be an electrolyte excludes liquid alloys of the metals through which the current is conducted as through solid conductors. Lastly, it should be carefully noted that the evidence of chemical action is only to be found at "*the places where the current enters and leaves*" the liquid conductor.

It has been already mentioned (page 15) that the decomposition of water by the electric current was discovered in 1800 by Nicholson and Carlisle, and that Davy in 1807 used this new method of analysis in his researches on the composition of the alkalies, during which he discovered and isolated the metals potassium and sodium.

Notwithstanding this striking instance of the value of the new method of analysis, the quantitative laws were not discovered and formulated until 1833, when Faraday in a series of brilliant experiments revealed them in all their simplicity and beauty. Previously the qualitative action, only, was known in a few typical cases. The most familiar one was that in which acidulated water was decomposed in an apparatus of which Fig. 161 shows a modern form. It consists essentially of two platinum plates, P and P′, immersed in a vessel containing acidulated water; the peculiar shape given to the containing vessel is solely for the purpose of more easily collecting the gaseous products of decomposition which are set free at these plates. There are two side tubes, S O and S′H, connected at the bottom by a short cross tube, P P′, from the centre of which rises a longer open tube terminating in a large bulb. The side tubes have stop-cocks, S and S′, at their upper ends, and with the central tube are usually graduated so that the contained volumes may be read off. The plates P and P′ are joined to the external binding screws T and T′ by platinum wires which are sealed through the glass. If now with the two side tubes full of acidulated water a current be passed through the apparatus from T to T′, bubbles of gas will appear on the two plates, and as they accumulate will become detached and float to the surface of the liquid in the respective tubes ; the liquid will be driven by the pressure of these gases out of the side tubes into the central one, in which the level of the liquid will rise. After some little time it will be noticed that the quantity of gas evolved from P is only about one-half of that liberated at P′, and it can be easily shown that the two gases are respectively oxygen and hydrogen, the constituents of water. Thus, if the stop-cock S be partially opened, the gas O will be driven out by the pressure of the liquid, and if a glowing splinter be held in the issuing gas it will be ignited, indicating the presence of oxygen gas. Again, if the stop-cock S′ be opened and the issuing gas H ignited, it will burn with the pale-bluish flame characteristic of hydrogen gas, and the water formed by combustion can be condensed on a cold plate held over the flame.

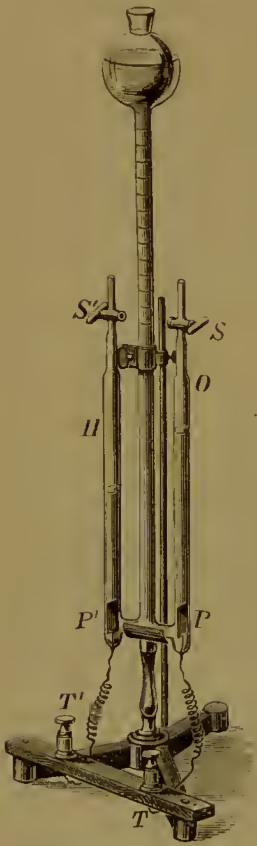

Fig. 161.—Hoffmann's Voltameter.

The above experiment may be regarded as a fundamental one, fully illustrative of the chemical action of the current, and will be useful for introducing the special *nomenclature* connected with this subject. This nomenclature was devised by Faraday, and is an exceedingly ingenious and convenient one. The process of decomposition by means of the electric current he called electric analysis, or, for brevity, **electrolysis**, and the liquid that is decomposed the **electrolyte**. The solid conductors P and P′, by which the current enters and leaves the liquid, he called **electrodes** (or electric paths[1]), the one by which it enters being for distinction called the **anode**[2] (up-path) and that by which it leaves the **kathode**[3] (down-path). The products of the electrolysis he called **ions** (the things which *go*[4]), that which appears at the anode being the **anion**, and the one which appears at the kathode, the **kation**. The complete apparatus Faraday called a *Volta-electrometer*, or, more shortly, a **Voltameter,** in honour of Volta, whose discoveries form the starting-point of the science of current electricity.

Secondary Actions.—It will be noticed that the liquid used in the Voltameter described on page 297 is specified as *acidulated* water, and not *pure* water; the latter, as we have seen, has such a high resistance as to be almost an insulator, but the addition of a very small quantity of sulphuric acid reduces its resistance considerably, and enables a moderate P.D. to drive a good current through it. The part played by the sulphuric acid is still somewhat obscure: it may merely render the water conductive, thus allowing the current to pass and decompose the water at the electrodes; in which case the chemical action would be represented by the single equation:—

$$H_2O = H_2 + O,$$

or Water *yields* Hydrogen and Oxygen.

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[1] Greek, ὁδὸς, *a way or path.*

[2] Greek, ἄνω, *upwards.*

[3] Greek, κατὰ, *downwards.*

[4] Greek, ἰὼν, *that which goes* (Neuter Participle).

But it is more than probable that the sulphuric acid is directly electrolysed, and that the oxygen evolved is a product of a purely chemical action, taking place subsequently to the electric action. According to this view we should express the action by the equations :—

$$H_2SO_4 = H_2 + SO_4,$$

Sulphuric Acid *yields* Hydrogen and Sulphion.

and

$$SO_4 + H_2O = H_2SO_4 + O,$$

Sulphion and Water *yield* Sulphuric Acid and Oxygen.

The first equation shows the reaction due to the electric current, which splits up the sulphuric acid into hydrogen gas and a compound known as sulphion, which cannot exist by itself in the presence of water, from which it takes the hydrogen, to re-form sulphuric acid, and sets free the oxygen ; the latter probably being a purely chemical reaction uninfluenced by the current. In whatever way we regard the mode of action, the final result is the same, namely, that hydrogen and oxygen are set free in the proportions in which they are combined to form water. We shall consider presently how it is they appear at places so far apart as the electrodes. Subsequent chemical actions, such as are referred to above, often accompany electrolysis ; they are known as *secondary actions*, and in consequence of them the products appearing at the electrodes are not always the *true ions* produced by the direct action of the current. More especially if electrodes are used which are acted on by the liberated ions or by the electrolyte, the true effects of the current are masked ; hence the reason for employing inert platinum plates in a water voltameter.

Ordinary hydrogen and oxygen unite to form water in the proportion of two volumes of hydrogen to one volume of oxygen, and hence in the voltameter the tube over the kathode will be found to contain about twice as much gas as the one over the anode. The proportion is not quite exact, because of the different solubilities of the two gases in water, and also because some *ozone*, which is a dense form of oxygen, is usually produced at the anode.

The hydrogen or *metallic* element is the one which appears at the kathode or plate connected to the negative pole of the battery; in other words, the *metal* hydrogen behaves as if it *travelled with the current.* Similarly, when other compounds are electrolysed the metallic part travels with the current and appears at the kathode. For instance, if the electrolyte be copper sulphate solution, or fused tin chloride, or fused potash, the metals copper, or tin, or potassium are set free at the kathode. Hence the *direction of the current* may be defined as that in which the *metallic ion* travels in a voltameter. It is often convenient to remember this simple rule, which is applicable not only to voltameters but also to secondary and primary batteries, giving rise in the latter, as we have seen, to the polarisation troubles at the negative plate, which corresponds to the kathode of the voltameter. Thus we get a deeper insight into the universality of the simple laws under which nature works, and the applicability of those laws to cases at first sight widely different and sometimes apparently contradictory to those in which the laws are most familiar to us.

Turning now to the *anode*, we find that the element or compound radical which appears there belongs to that class of bodies which chemists regard as *non-metals*, or bodies whose properties are analogous to the non-metals. One of these properties is a *chemical affinity*, as it is called, for the metals. The more important of these *electro-negative* bodies, or *anions*, are oxygen, chlorine, bromine, iodine, cyanogen (CN), sulphion (SO_4), etc. As *ions* they travel against the conventional direction of the current, and appear at that point where it enters the liquid, either in a voltameter or in a galvanic cell. Thus, in a cell with zinc as the positive element and dilute sulphuric acid as the exciting liquid, we have the current flowing into the liquid from the zinc, and therefore electrolytically oxygen or sulphion is separated at the zinc plate, and at once combines with the zinc, setting free the chemical energy which, as already explained (page 28), re-appears as the energy of the current.

Now it may appear contradictory to say in one place that it is the dissolution of the zinc which gives rise to the current, and in another that the flow of the current causes the dissolution of the zinc. The fact is that we are here dealing with the actions of *molecules*, if not of *atoms*, and our limited senses are quite unable to observe the actions of individual molecules. To us all the phenomena described seem to take place simultaneously, and it would almost appear as if it would be impossible to discover the exact order until we can make observations on single molecules; for the present we can but speculate upon it.

FARADAY'S LAWS OF ELECTROLYSIS.

The main quantitative laws of Electrolysis, or the chemical action of the electric current as enunciated after laborious investigation by Faraday, are exceedingly simple. His general statement, which includes explicitly or implicitly the various laws, is thus given in his "Experimental Researches"[1]:—"*For a constant quantity of electricity, whatever the decomposing conductor may be, whether water, saline solutions, acids, fused bodies, etc., the amount of electro-chemical action is also a constant quantity, i.e., would always be equivalent to a standard chemical effect founded upon ordinary chemical affinity.*" Before considering this statement in detail a few preliminary remarks may be advisable.

In talking about "polarisation" (pp. 43 to 49) we have already referred to some of the chemical laws which regulate the combinations of various elements to form compounds.

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[1] Series V., par. 505 (June, 1833).

For the present purpose the most important of these is the beautiful law of *chemical equivalents*, according to which each element in combining with other elements does so in definite numerical proportions. Thus sodium in combining with chlorine to form common salt does not enter into combination in a haphazard way, any amount of sodium entering into combination with any amount of chlorine which happens to be present. On the contrary, it is found that 46 parts of sodium by weight always combine with 71 parts of chlorine, no more and no less. If there is too much sodium or too much chlorine for this proportion, some of the element which is in excess remains uncombined. Similarly 46 parts by weight of sodium always combine with 16 of oxygen to form the oxide of sodium, and 16 parts of oxygen combine with 2 of hydrogen to form water.

To the accurate determination of these equivalent numbers, or "equivalents," chemists have devoted an enormous amount of labour and care. The results for various metals have been already given in the second columns of the three tables on heats of combination (pages 45 *et seq.*); in those columns the numbers are the weights of the various metals which combine with or are equivalent to 16 grams of oxygen. Referring to Faraday's statement, they are the weights of the various metals, "founded upon ordinary chemical affinity," which enter into any electrochemical action in which 16 grams of oxygen play a part.

This action Faraday's statement affirms is always brought about by a "constant quantity of electricity," and it is obvious that such a constant quantity of electricity might be taken as the *unit quantity* for measuring other quantities of electricity. A unit of this kind would be the most natural from the point of view of electrolytic action. Unfortunately for simplicity in electrolytic calculation, the *unit quantity* of electricity is dependent on the definition of the *unit current* (unit quantity per second), and the latter is most conveniently defined by its magnetic action, given subsequently (page 372). The amount of oxygen produced in a water voltameter by the corresponding unit quantity (*i.e.*, unit current flowing for one second) is neither 16 grams nor 1 gram, but 0·0000828 gram. This last number is called the *electro-chemical equivalent* of oxygen, and the numbers for all the other elements have to be altered to correspond with it. Thus we have two sets of numbers, (1) the ordinary *equivalents* used by chemists, which are simply *ratios*; and (2) the *electro-chemical equivalents*, which have the same ratios to one another as the first set, but are *definite weights*, giving the actual amount of the element either set free or entering into combination during the passage of one **coulomb** (the unit quantity) of electricity. These numbers are set forth in the following table :—

TABLE VII.—ELECTRO-CHEMICAL EQUIVALENTS.

Element.	Chemical Equivalent.	Electro-Chemical Equivalent.
Hydrogen	2	·00001038 gramme.
Nitrogen[1]	9·3	·0000481 ,,
Oxygen	16	·0000828 ,,
Aluminium	18	·0000932 ,,
Magnesium	24	·0001242 ,,
Calcium	40	·0002070 ,,
Sodium	46	·000238 ,,
Iron (ferrous)	56	·000289 ,,
,, (ferric)	37·3	·000193 ,,
Cobalt	59	·000305 ,,
Nickel	59	·000305 ,,
Copper	63	·000326 ,,
Zinc	65·5	·000339 ,,
Chlorine	70·7	·000366 ,,
Potassium	78	·000404 ,,
Tin	118	·000611 ,,
Bromine	159·5	·000825 ,,
Mercury (mercuric)	200	·00104 ,,
,, (mercurous)	400	·00208 ,,
Lead	207	·00107 ,,
Silver	216	·001118 ,,
Iodine	253	·00130 ,,

[1] The names printed in italics indicate non-metallic or *electro-negative* bodies.

Conversely, any of the numbers in the last column of this table may be taken to form the basis of a definition of the unit quantity of electricity, and, therefore, of unit current; and such a definition is *in practice* more convenient than the electro-magnetic one to be given presently. In fact, it is of such practical convenience that it is one of the definitions adopted by the Board of Trade in dealing with electrical units. It may be stated thus:—

Definition of Unit Electric Current.—*A current of* **one ampère** *is the* **steady** *current which, when passed through a silver voltameter,*[1] *deposits silver at the rate of* 0·001118 *of a gramme per second.* To this we may add:—

Definition of Unit Quantity of Electricity.—*One* **coulomb** *is that quantity of electricity which, passing in a definite direction through a silver voltameter,*[1] *deposits* 0·001118 *of a gramme of silver.*

The second definition is simpler than the first, and is the one led up to directly by electrolytic laws; for the amount of chemical action in a voltameter depends only on the total quantity of electricity that passes through, and not at all upon the time. Thus a voltameter can only measure *currents* when they are *steady* for a sufficiently long time; but however fluctuating a current may be (provided it is never reversed), a suitable voltameter placed in the current will measure the total number of *coulombs* of electricity that have passed.

We can now re-state Faraday's laws in a more detailed form, which we think our readers will be able to follow more easily:—

Law I.—The quantity of an *ion* liberated in a given time is proportional to the total quantity of electricity that has passed through the voltameter in that time.

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[1] Described at p. 331.

Law II.—The quantity of an *ion* liberated in a voltameter is *proportional* to the electro-chemical equivalent of the *ion*.

Law III.—The quantity of an *ion* liberated is *equal* to the electro-chemical equivalent of the *ion* multiplied by the total quantity of electricity that has passed through the voltameter.

We must not leave this part of the subject without pointing out that all details connected with the dimensions of the apparatus are omitted in the above statement of the laws; indeed it is the possibility of omitting these details that constitutes their simplicity, and the greater part of Faraday's work was directed to proving that wide variations in these omitted details had no effect on the result.

The unspecified particulars which do not affect the laws may be briefly summarised as follows :—

(*a*) the absolute magnitude of the current.
(*b*) the P.D. at the terminals of the voltameter.
(*c*) the size and distance apart of the electrodes.
(*d*) the strength of the solution.
(*e*) the source of the current.

With regard to the first four, the values are non-essential only *within wide limits*, and in practical voltameters the disregard of them must not be pushed too far, because of secondary actions, which, although they do not alter the truth of the laws, interfere with their practical application. The last (*e*) constitutes one of the strongest proofs that all currents of electricity, no matter from what source they may be derived, have absolutely identical properties.

THEORIES OF ELECTROLYSIS.

When we consider the beauty and interest of the experimental results attained by electrolysis, how in the hands of Davy, Faraday, and others it has extended our knowledge of the nature of many compound bodies, revealed to us new elements, and given us new compounds, we are not surprised that philosophers have hopefully looked to it to reveal to them still greater depths of the mysteries of nature. Thus the phenomena of electrolysis have afforded, ever since their discovery, a fascinating field of speculation, not only upon the molecular mechanism by which the various changes are brought about, but also upon the nature of electricity itself, and the constitution and structure of atoms and molecules. There are still many problems connected with the subject which are far from being satisfactorily solved; but, without going into recondite matters, it may be interesting to consider very briefly some of the principal theories that have been advanced from time to time to account for the facts.

The earliest plausible theory is probably that of Grotthuss, who in 1806 published some speculations on the subject. He considered that the two electrodes connected to the battery were thereby endowed with attracting and repelling properties. For instance, the kathode was said to attract hydrogen and repel oxygen, whilst the anode had the opposite property of attracting oxygen and repelling hydrogen. Thus each molecule of water found itself under the action of forces which tended to drag its hydrogen and oxygen atoms in opposite directions. The first effect of this would be to set the molecules with their hydrogen ends (if we may so regard a molecule) turned towards the kathode, and their oxygen ends turned towards the anode. This is represented in the annexed figure. Row 1 is meant to represent a set of molecules with their heads indifferently turned in all directions before the battery wires are joined up. The shaded parts of the ellipses are intended to represent the hydrogen or electro-positive ends of the molecules, and the unshaded parts the oxygen or electro-negative ends. Row 2 is supposed to represent the first effect of completing the battery circuit, all the shaded parts being turned to the right and the unshaded parts to the left. Then it is supposed that each molecule is torn asunder, under the action of the electric attractions and repulsions, the hydrogen part moving towards the kathode B, and the oxygen part toward the anode A. But in the middle of the liquid the hydrogen of any molecule meets the oxygen of the molecule on the right coming the other way, and immediately combines with it to form a new molecule of water, as shown in row 3. Thus only the hydrogen of the molecule next to B, and the oxygen of the molecule next to A, are unable to find new partners, and appear on the respective electrodes as free gases.

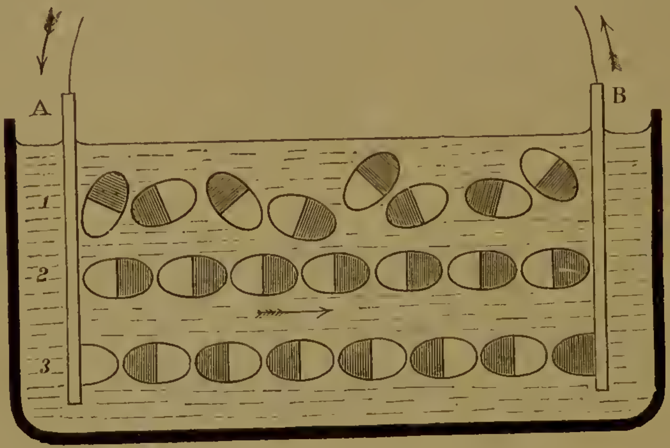

Fig. 162.—Explanation of Electrolysis.

It should be noticed that this theory supposes that decompositions take place throughout the liquid between the electrodes, but except at the latter the decompositions are immediately followed by recombinations, so that it is only at the electrodes that evidences of decomposition appear.

With this view of the matter Faraday agrees, but he differs from Grotthuss in ascribing the active cause, not to the attraction and repulsion of the electrodes acting at a distance, but to internal molecular forces called into play by the passage of the current. Here is what he says:[1]—"I conceive the effects to arise from forces which are *internal*, relative to the matter under decomposition, and not *external*, as they might be considered if directly dependent on the poles. I suppose that the effects are due to a modification, by the electric current, of the chemical affinity of the particles through or by which the current is passing, giving them the power of acting more forcibly in one direction than in another, and consequently making them travel by a series of successive decompositions and recompositions in opposite directions, and finally causing their expulsion or exclusion at the boundaries of the body under decomposition, in the direction of the current, *and that* in larger or smaller quantities, according as the current is more or less powerful."

Faraday went a step further, and maintained that conduction in electrolytes *only* takes place by means of electrolysis—that is, by the decompositions and recompositions already referred to. But, as we have shown when dealing with the theory of primary and secondary batteries, to effect a given decomposition electrically requires a definite electric pressure depending upon the potential chemical energy of the separated ions. Therefore to force a current through a water voltameter should require a battery with an E.M.F. of not less than 1·56 volts, the electric pressure of hydrogen in an oxydising medium.[2] Until this pressure is reached, therefore, there should be no current, for until then there can be no electrolytic decomposition. Faraday, however, himself showed that a single Daniell's cell (E.M.F. = 1·08 volts) could maintain a *very weak* current for many days through a water voltameter, although there was no appearance of gas at the electrodes.

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[1] *Experimental Researches*, Series V., par. 524 (June, 1833). The italics are Faraday's.

[2] *Vide* Table I., p. 45.

Helmholtz has more recently shown that this very weak current entirely ceases if certain precautions are taken. When these precautions are not observed, he supposes the feeble current which passes to be due to the presence of small quantities of free oxygen and hydrogen, which are usually in solution in most liquids exposed to air.

Clausius explains the known facts in a different manner, based upon the kinetic theory of the constitution of liquids, according to which the molecules of all liquids are necessarily in motion and colliding with one another, the mean velocity increasing with rise of temperature. Even at low temperatures, however, he supposes that some of the individual collisions are sufficiently violent to break up the colliding molecules into their constituent atoms, which go rambling in the free state through the liquid until they meet with new partners, with whom they combine. It is upon these wandering atoms, and not upon the molecules, that, as he maintains, the electric action is effective, causing their paths to be deflected from what they would otherwise have been, so that, on the whole, the electro-positive atoms move towards the kathode and the electro-negative ones towards the anode. Since the velocity of molecular motion, and therefore the frequency and violence of the collisions increase when the temperature rises, we should expect, if Clausius' theory be correct, that the conductivity of electrolytes should increase with the temperature, since at a high temperature there must be more free atoms in the liquid than at a low one. That the conductivity does rise with the temperature is a well-known experimental fact, electrolytes in this respect differing from metals whose conductivity is less at a high temperature than at a low one. Clausius' theory, therefore, though not absolutely and conclusively proved, offers a highly probable explanation of the known facts.

2. Laws of Thermal Action.

The statement of the laws of the "thermal" action of the electric current will not detain us long. The brevity of the treatment is not, however, due to any lack of interest or of beauty in the phenomena involved, but because if we were to follow the thermal effects into all their consequences in the numerous cases in which they are manifested, we should well-nigh have to lay before our readers a treatise on the cognate science of "Heat." We shall, therefore, confine ourselves to considering the laws governing only the *production* of heat in a current-carrying conductor.

In a subsequent part of the book we shall consider some of the uses made of this production of heat—as, for instance, electric lighting, heating, and welding; as well as, more briefly, how it may be applied to the measurement of the current. The laws of production only will be dealt with at present.

The law governing the rate of production of heat by the current was first clearly expounded by Joule, and is usually known as **Joule's Law.** It may be enunciated thus:—*The* **rate** *of production of heat by an electric current passing through a resistance is proportional to the* **resistance** *and to the* **square of the current.** In this enunciation the current is supposed to have been already defined by either its magnetic or chemical effect, and it is to the *square* of the current so defined that the rate of production of heat is proportional.

A curious line of reasoning led Joule to predict this law. Experiment shows that if a certain current be passed through a certain wire, the rate of production of heat is the same *whichever way the current be passed through the wire.* In this respect the thermal effect differs from the magnetic and chemical effects, which are both reversed if the current be reversed. If the thermal effect were similarly reversed we should have the production of heat, or *heating*, when the current is passed one way through the wire, and the absorption of heat, or *cooling*, when the current is passed the other way through. Such, however, is not the case; the effect is always a heating effect, *and increases with the increase of the current.* Now, algebraically, the *square of a negative* quantity gives the same *positive* result as the *square of a positive* quantity of the same numerical magnitude. Since, therefore, the change of the current from positive to negative produces no change in the effect, Joule concluded that that effect must be proportional to the square[1] of the current. Experiment has abundantly confirmed this ingenious prediction.

Joule's Law also asserts that the rate of production of heat *of a given current* is proportional to the resistance of the conductor. It is this fact that gives to the word *resistance* its appropriateness as a name for this particular property of conductors. For, as we have just seen, and as we have before[2] explained, this production of heat is of the same nature as all *frictional* productions of heat, inasmuch as the process is *irreversible.* So important is this view of the matter that it is perhaps more philosophical to define resistance by reference to the heat produced, instead of defining it as the ratio of potential difference to current. From this point of view resistance would be defined as the ratio

$$\frac{\text{Heat generated per second in the conductor}}{\text{Square of the current transmitted.}}$$

And this definition of resistance becomes of value, as we shall see later on, when we have to deal with fluctuating or alternating currents.

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[1] It is true that every *even* power of a negative quantity is positive, but Joule showed that none of the higher powers above the second (or square) was concerned in the effect.

[2] *Vide* p. 244.

It follows that if the same current be successively passed through wires of the same diameter but of different materials, those wires which have the highest specific resistance, and therefore the highest actual resistance for any given length, will become hotter than those of lower specific resistance. A pretty experiment to illustrate this is shown in Fig. 163, in which a chain, consisting of alternate links of platinum (*Pt*) and silver (*Ag*) made of the same gauge of wire, is stretched between two conducting posts. When a suitable current is passed along the chain, the platinum links become red-hot, whilst the silver ones remain cool and dark because of their lower resistance.

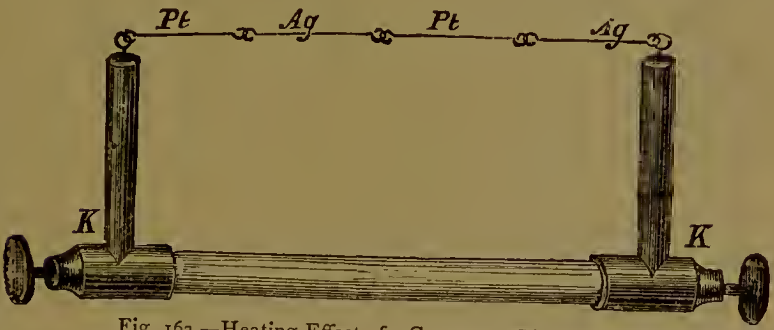

Fig. 163.—Heating Effect of a Current on Platinum and Silver.

So far we have dealt only with the *rate* of production of heat in a conductor through which a current is flowing. If the current *be steady* the *rate* of production is steady, and the *total* heat produced in a given time is *proportional* to the time. It ought, therefore, to be possible to express the heat produced, as measured in ordinary heat units, in terms of the current, the resistance, and the time. This can easily be done. If H be the *total* heat generated in a given time, *t*, measured in *seconds*, by a current of A *ampères*, flowing through a conductor whose resistance is R *ohms*, we have :—

$$H = 0{\cdot}24\ A^2Rt.$$

In this equation the heat is measured in *calories*,[1] and the multiplier 0·24 is necessary in order that the result may appear in these the ordinary heat units. If this multiplier is omitted, the quantity of heat will be given in *Joules* ;[2] and if it be required in other units, other multipliers must be used.

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[1] *Vide* p. 28.

[2] *Vide* p. 413.

CHAPTER VIII.

LAWS OF MAGNETIC ACTION.

In the chapter upon the "Mechanical Production of the Current" we have dealt in detail (pp. 138 to 151) upon several of the aspects under which the magnetic action of the current may be viewed, and we have traced the consequences of that action in several important cases. In doing this we have employed throughout Faraday's theory of the magnetic strains and stresses which we know exist in the medium, whatever that may be, in which the conductor carrying the current is immersed, the stresses being graphically represented by the "Lines of Force" which we have used freely. In connection with this method of viewing the phenomena, there remains, within the scope of this work, little else to be given but the numerical data with which experiment has supplied us.

But the consideration of the magnetic action of the current would be incomplete without some reference to the brilliant discoveries of Ampère on the mutual actions of currents on one another, and of magnets on currents; experiments which were made ten years earlier than Faraday's. In the form in which these experiments were first given to the world, they were accompanied by a complete mathematical analysis and explanation, based upon certain probable assumptions, in which the action of the medium was ignored, being replaced by theories of direct action at a distance. With the action of magnets on currents, discovered by Ampère, we shall not now concern ourselves, but refer the reader to page 140, in which ways of showing the action are described. The action in any other given case can be readily deduced.

The currents available for experiment in the early part of this century, being produced by primary batteries, were small compared with those that can now be placed at the disposal of the physicist; consequently the various effects of the currents were correspondingly small, and of these effects the mechanical action on one another of two straight conductors carrying such currents is very minute. Had it been at all comparable with the mechanical action between two well-magnetised pieces of steel, its discovery would probably have followed more quickly upon the discovery of methods of maintaining a continuous current in a circuit. To detect the action, the conductor acted upon must therefore be very free to move. But electric currents only flow in closed circuits, one part of which must include the battery or dynamo or other seat of the E.M.F. Unless, therefore, we are prepared to make the whole circuit movable, as was afterwards done by De La Rive, some form of sliding connection between the fixed and the movable part of the circuit must be devised, and this sliding connection must be very free from friction. One of Ampère's ingenious devices for accomplishing this is shown in Fig. 164.

The wooden pillar, B, has two concentric grooves at its upper end, which hold mercury, into which the ends, x, y, of the circular conductor dip. This circular conductor is supported by an insulating pillar, C, by means of a needle point attached to the highest part of the conductor, and resting in a hollow cup at the top of C. One of the concentric rings of mercury is connected by copper strips through a commutator (on the left) to the terminal marked +, and the other to the terminal marked −. From these terminals a current can be passed in the direction of the arrows through the circular conductor, which is very free to rotate round the vertical axis, C.

A circle so mounted will, as we have previously shown, set itself with its plane at right angles to the earth's magnetic meridian when the current flows, and it is held in that position by a force which, though small in itself, is great compared with that exerted on it by any other simple conductor in its neighbourhood, carrying a current of the same order of magnitude. To observe the latter effect it is, therefore, necessary to devise some means of eliminating or neutralising the earth's magnetic action. This Ampère accomplished by using the astatic rectangles shown in Figs. 165 and 166. The principle employed is to make the movable part of the circuit consist of two rectangles in the same plane, of about equal area, joined in series with one another in such a way that if the current flows in a clock-wise direction round one, it flows counter-clockwise round the other. If these rectangles be then symmetrically mounted with regard to the axis of rotation, the earth will tend to turn them in opposite directions with equal efforts, and any

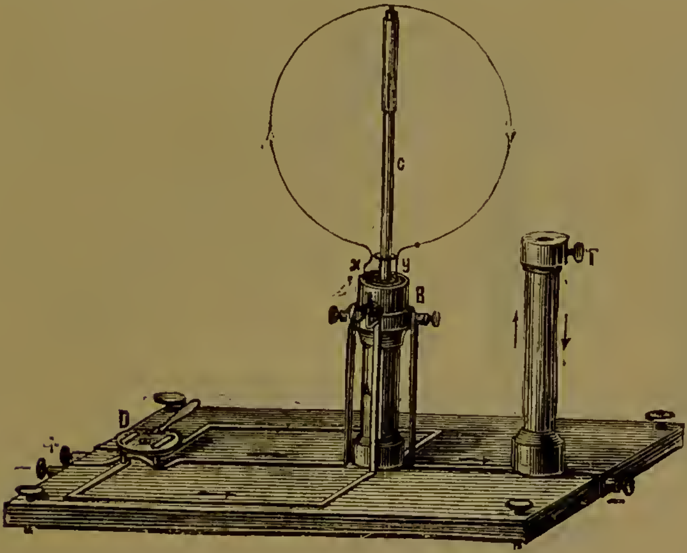

Fig. 164.—Ampère's Circle.

tendency of one of them to rotate will be counterbalanced by the opposite tendency of the other. The movable framework will, therefore, remain indifferently in any position in which it happens to be in when the current starts. The movable rectangles in Fig. 165 are suspended from the mercury cups *a* and *b*, and these are joined to the rest of the circuit by means of the stiff wires and the mercury cups A and B in the base. Now let another wire carrying a current be brought up parallel to one of the outer vertical sides of the framework; it will be found that if the two currents are both going in the *same direction*, say downwards, as in the figure, they will *attract* one another. But if the nearest currents are in *opposite directions*, say one upwards and the other downwards, there will be *repulsion*. From experiments of this kind Ampère deduced the law:—*Two*

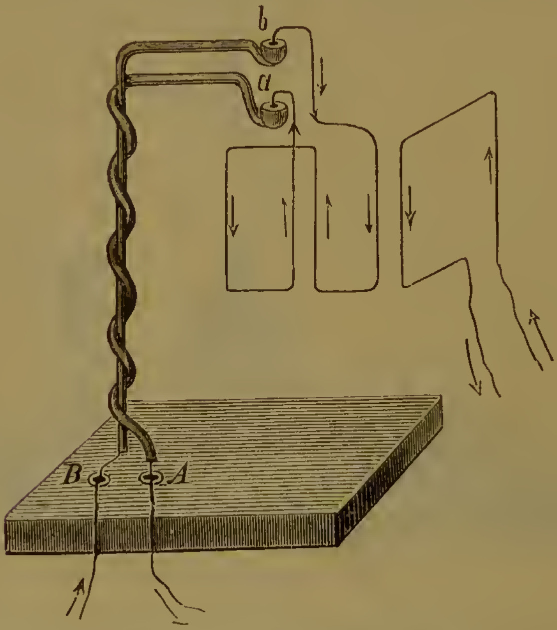

Fig. 165.—Action of Parallel Currents.

parallel straight conductors attract or repel each other according as the currents in them have the same or opposite directions.

When the conductors are not parallel, there may still be attraction or repulsion which may be demonstrated by means of the apparatus shown in Fig. 166. In this case the astatic rectangles are suspended from the cup *a*, at the top of the upright pillar, and are joined to the outer circuit by the wires *x* and *y*, dipping into the concentric mercury cups contained in the base B; these mercury cups are metallically connected to appropriate terminals not shown. In the fixed conductor the current is brought up the outside of the tube *b*, and after pursuing the path figured, is taken away down a central wire insulated from the outer tube. The action that will be observed is that *the movable conductor will always strive to set itself so that its current is* PARALLEL *to and in the* SAME DIRECTION *as the current in the fixed conductor*.

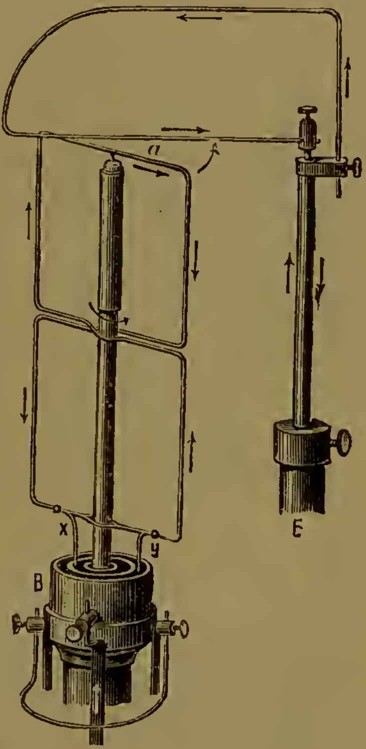

Fig. 166.—Action of Inclined Currents.

If the two conductors be accurately at right angles, there will be no action, but the mechanical momentum that will be acquired by the movable framework will be sufficient to carry it past this "dead-point" if it be necessary to pass through it in order to take up the above position.

Ampère showed mathematically that all the above actions could be deduced from an elementary law, in which it was assumed that each little bit of one circuit acted upon each little bit of the other with a *force proportional to the currents in them, and inversely as the square of the distance between them*, due allowance being made for the relative directions of the little bits. In connection with this celebrated law it must be remembered that we cannot experiment upon little bits of circuits taken by themselves, but only on completely closed circuits. Since Ampère's time it has been shown that the experiments can be explained by assuming other laws for the action of the little bits on one another. But the greatest omission in Ampère's theory is its neglect of any allowance for the action of the medium. The experiments were made in air, and the use of iron and magnetic materials was carefully avoided in the construction of the apparatus. If iron be introduced between the two circuits, the actions that take place are quite different, and depend upon the mass, shape and permeability of the iron. In fact, the attractions and repulsions are due to the magnetic stresses of the medium surrounding the circuits, and can be explained by reference to the Lines of Force, according to the rules already given.

Lines and Tubes of Force.

We do not propose to consider the numerical details of the magnetic action of currents and magnets as based upon action-at-a-distance theories, but shall proceed to show, in a general way, how Faraday's theory of the action, being due to stresses and strains in the medium, may be subjected to calculation. On page 110 we have given Faraday's definition of the "magnetic curves," and have hinted that the lines may be so drawn as to indicate, not only the direction, but also the magnitude of the forces at the different parts of the magnetic field. How this may be done will now be shown as simply as possible.

Experiment indicates that the magnetic action of a current (or of a magnet, which is equivalent, for our present purpose, to some distribution of currents) on the surrounding medium is that of a stretching force or *tension* along the lines of force, and a squeeze or *pressure* in all directions at right angles to them. The reactions or stresses set up in the medium or ether, as we shall call it, are, of course, equal and opposite to these impressed forces, and therefore consist of a tendency to *contract* along the lines of force, and *expand* at right angles to them. Hence our assertion on p. 115 that the lines of force tend "to grow shorter in the direction of their lengths, but to repel one another sideways." In fact, taking any straight portion of a line of force, the ether immediately surrounding it is in much the same state as a stretched cord of india-rubber, which, as soon as the forces stretching it are suppressed, will contract to its original length, and expand sideways to its original cross-sectional area. But in using this illustration we must caution our readers against supposing that the ether can be stretched or squeezed to anything like the same extent as indiarubber. All experiments show that the ether is highly unstretchable and incompressible, and that an extremely slight amount of stretch or squeeze calls into play enormous forces of restitution. Bearing this caution in mind we may use our stretched rubber cord to illustrate the strained condition of the ether.

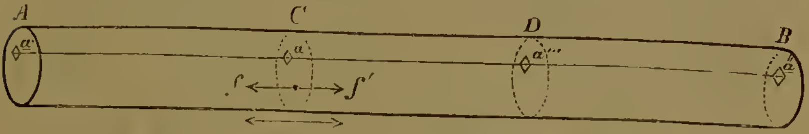

Fig. 167.—Line of Force in Stretched Rubber Cord.

Let A B (Fig. 167) represent a portion of a rubber cord stretched in the direction of its length by means of appliances not shown in the figure. At every cross-section, C, perpendicular to its length, there will be innumerable little forces in action, such as f and f', which tend to tear the two sides of the cross-section asunder; these forces will be counterbalanced by the internal stresses between the two sides of the section. Now, these forces being distributed all over the section, according to some law, it is evident that we can divide the section into a number of little areas, such as a, of any convenient shape, but which have this property in common, viz., that the sum of all the little forces on one side of the area is equal to the unit of force (the dyne, or the pound weight, or whatever unit may be convenient). If, now, all the boundaries of these small areas be extended in the direction of the length of the cord, so as to run always along the lines of the stress (or force), the whole substance of the cord will be divided into a number of tubes whose ends will appear on the two terminal faces, A and B. Thus the ends of the tube passing through the boundary of a will be a' on A, and a'' on B. Such tubes are called **Tubes of Force**, and the method of drawing them shows that if we consider any cross-section of the cord, such as D, the sum of the forces acting across the section a''' of any tube is equal to the unit of force. Where, therefore, the forces are great, the areas of the tubes will be small, and where the forces are small the areas will be large. Consequently, for great forces the tubes are numerous, but diminish in number as the forces diminish. Now, if we *replace each tube* by a *line drawn along its axis*, these lines will be drawn along the **Lines of Force**, and by their distance apart will graphically represent the magnitude of the forces at each point. Where the lines are close together they will correspond to narrow tubes and great forces; where they are wide apart they will correspond to wide tubes and small forces.

Similarly the space of the magnetic field can be divided into tubes and Lines of Force, and it will be to lines so drawn that we shall now always refer when we speak of the "number" of Lines of Force in any magnetic field. It will be obvious that, if in such a field we place a small area, say of cardboard, at right angles to the Lines of Force, the total force acting across the area of the card (not, however, *on* the card) will be equal to the total number of the Lines of Force that pass through the card. It will, of course, be understood that in the magnetic case the unit of dynamical force used in the india-rubber illustration is replaced by the unit of magnetic force defined on page 111.

The Magnetic Circuit.

We have dwelt so fully on the properties of the magnetic circuit in the preceding pages (210 to 213) that little remains to be referred to here beyond the methods of expressing the various quantities in exact numbers. The three chief quantities with which we are concerned are the "Magnetomotive Force," the "Total Flux," or total number of closed lines in the magnetic circuit, and the "Magnetic Reluctance" of the circuit. These quantities are connected by the simple relation :—

$$\text{Magnetic Reluctance} = \frac{\text{Magnetomotive Force.}}{\text{Total Flux.}}$$

or otherwise :—

$$\text{Magnetomotive Force} = (\text{Total Flux}) \times (\text{Magnetic Reluctance.})$$

It is in the latter form that the relation is most frequently required, for the usual problem is to find the Magnetomotive Force that will be required to produce a certain number of magnetic lines or Flux in a given circuit.

On page 150 we have stated that the *Magnetomotive Force* is proportional to the product of the current by the number of times it is looped (see Fig. 77) through the magnetic circuit. If the current is measured in ampères, this product is known as the "ampère-turns," and the Magnetomotive

Force is proportional to the ampère-turns. The exact connection is:—

$$\text{Magnetomotive Force} = \frac{4 \times 3{\cdot}142}{10} \times (\text{Ampère-turns})$$
$$= 1{\cdot}257 \times \text{Ampères} \times \text{Turns},$$

or very nearly $1\frac{1}{4}$ times the number of ampère-turns. Reciprocally, if the required Magnetomotive Force be known the ampère-turns can be calculated, and the method of winding an electromagnet for a given source of current can be worked out.

The quantitative meaning attached to the term "Lines of Force" has just been carefully explained. By the term *Total Flux* is simply meant the total number of lines of force, drawn in the manner set forth, which are present in the field. These Lines of Force, it must always be remembered, are closed curves. In the magnetic curcuit of a dynamo machine we have to deal with millions of such lines.

The physical meaning of the term *Magnetic Reluctance* has been explained at page 151. Its numerical value, however, is not easily calculated. It depends upon the permeability, the cross-section of the circuit perpendicular to the lines, and the length of the lines. All these factors may, and usually do, vary greatly in different parts of the circuit, and hence there arises the difficulty of the calculation. The principle of the calculation is, however, easily grasped; it is similar to the calculation of the electric resistance of a conductor from its dimensions and the known specific resistance of its material. Thus the reluctance of any piece of the circuit of uniform cross-section and permeability is proportional to its length, and inversely proportional to its permeability and cross-section, or in symbols:—

$$\text{Reluctance} = \frac{l}{\mu A}$$

where l and A stand for length and cross-sectional area, and μ stands for permeability. The similarity of this formula to that already given (p. 285) for the calculation of resistance is obvious. For the full calculation the whole circuit must be divided into pieces to which the above conditions apply, and the value of the reluctance must be calculated for each piece; the results have then to be combined according to rules similar to those given on pages 287 and 289, for the calculation of resistances joined in parallel and series. Where the circuit contains no magnetic material the value of μ is 1, and the calculation is simplified, though even then the calculation is by no means an easy one. But where the lines run through magnetic materials the values of μ have to be ascertained from records of the results of previous experiments collected in tables or graphically depicted in curves such as are shown in Fig. 75.

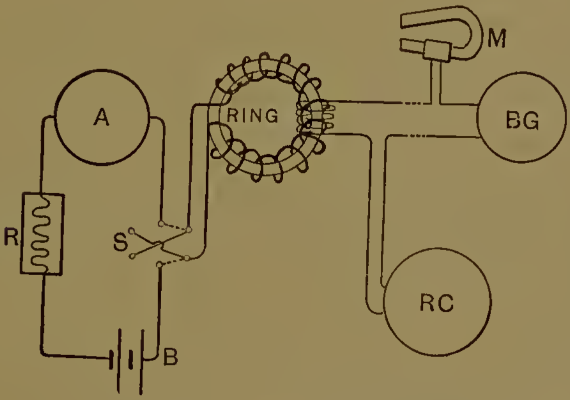

Fig. 168.—Measurement of Permeability.

This measurement of the values of μ for different magnetic materials under different conditions of saturation is, therefore, of the highest importance in electro-magnetic work, and we shall briefly describe one method out of many by which these values may be ascertained.

Fig. 168 shows diagrammatically the arrangement of the apparatus. The material to be tested is made in the form of a ring of uniform cross-section and over-wound with a coil of insulated copper wire, as shown by the thick line in the figure. The ends of this wire are brought to a reversing key, S, by means of which the current from the battery, B, can be set round the wire on the ring in either direction at pleasure. R is an adjustable resistance and A is an ampère-meter for measuring in ampères the current sent round the coils on the ring. As the number of turns in these coils can be counted, the ampère-turns used to magnetise the ring, and, therefore, the Magnetomotive Force, are known. To measure the Total Flux produced by this Magnetomotive Force a known number of turns of fine wire, forming a secondary coil, are wound round one part of the ring, and these are placed in closed-circuit with a ballistic galvanometer (*see* page 359), B G. When the current in the battery circuit is suddenly turned on, a number of magnetic lines are threaded through this small coil, and according to the principles of magneto-electric induction, the change in the magnetic flux gives rise to a transient induced E.M.F. in the coil, and a corresponding transient current in the galvanometer. From the movement of the galvanometer needle the value of the E.M.F., and, therefore, the number of lines threaded through, can be inferred. The ratio of the Magnetomotive Force to this Total Flux gives the reluctance of the ring, and a simple calculation gives the permeability of the material. The curves of permeability given in Fig. 75 were obtained thus by Dr. J. Hopkinson.

Magneto-Electric Induction.

When dealing with Faraday's discovery of Magneto-electric Induction we showed (page 173) that the currents induced in a circuit under induction depended upon the rapidity with which magnetic lines of force were withdrawn from or threaded into the circuit. The currents are due to

E.M.F.'s set up in the conductor by the addition or subtraction of the lines, and now that we have attached a precise and definite meaning to the rather vague phrase "number of lines of force," the magnitude of these E.M.F.'s can be calculated by the following very simple rule :—*The induced Electromotive Force in a circuit at any instant is proportional to the* **rate** *at which the magnetic lines of force are being withdrawn from the circuit.* To give the E.M.F. in volts the above rate has to be divided by 100,000,000 or 10^8, and thus we have the equation :—

$$\text{Induced E.M.F. in volts} = -\frac{1}{10^8} \cdot \frac{dN}{dt},$$

where dN represents the change in the number of lines which takes place in the time dt, and, therefore, the fraction $\frac{dN}{dt}$, gives the *rate* of change. Thus, if we are withdrawing lines from the circuit at the rate of 100 million per second, the induced Electromotive Force will be exactly one volt. This is the rate at which the conductors on the armature of a dynamo machine must cut the lines of force of the field magnet in order to produce even such a low electric pressure as one volt; hence arises the necessity for using powerful field magnets, with millions of lines crossing from one pole to the other.

To apply the rule to calculate the E.M.F. of a dynamo machine we would remind our readers that we have shown on page 178 that the above law for the E.M.F. in a closed circuit under magneto-electric induction leads to the following law for the E.M.F. in *any* conductor cutting lines of force :—*Whenever a conductor cuts lines of force, an E.M.F. is set up in the conductor at the place where the lines of force cut across it.* To this we may now add the quantitative rule, that *the E.M.F. set up is equal, in volts, to the* **rate** *of cutting of the lines of force divided by* 10^8.

As an example of the application of the rule we shall take the case of a two-pole continuous-current dynamo, and we shall suppose that

C = the number of conductors counted all round the outside periphery of the armature.
N = the total number of lines passing *through* the armature from one pole to the other.
n = the number of revolutions of the armature *per second.*

Now, in each complete revolution each conductor cuts every one of the N lines twice over, and, therefore—

$2N$ = number of lines cut by each conductor in *each* revolution.
Hence $2CN$ = the number of lines cut by all the conductors in each revolution.
And $2nCN$ = the *rate* at which *all* the conductors taken together are cutting lines of force.

This expression ($2nCN$) divided by 10^8 would, therefore, be the E.M.F. of the dynamo, if the electrical connections were such that the E.M.F.'s in all the conductors were added together. We have, however, shown (page 200) that it is not so, but that the conductors in one-half of the armature are in "parallel" instead of being in "series" with those of the other half. The effective E.M.F. is, therefore, only that of one-half of the armature, and thus we finally obtain the equation :—

$$\text{E.M.F. (in volts)} = \frac{nCN}{10^8}.$$

This simple method of calculating the E.M.F. of a dynamo machine is due to Dr. Silvanus P. Thompson.

We may remark that the formula is applicable to both "ring" and "drum" armatures, for the quantity C only takes account of the conductors on the *outside* of the periphery. The general rules can be applied to calculate the E.M.F. of multipolar and alternate-current machines, but the above example is sufficient for our purpose.

CHAPTER IX.

ELECTRICAL MEASUREMENTS.

In this chapter it is proposed to consider in detail the various methods by which the different quantities encountered in electrical phenomena are accurately or practically measured. We deliberately propose to devote a moderate amount of space to this part of the subject, because, not only is it a fascinating one in itself, but also because the study of the principles involved, and the modifications necessitated by practice in the design of the different beautiful instruments employed, will amply repay our readers, by endowing them with a juster appreciation of the wonders, as well as the limitations, of the various phenomena dealt with. At the same time, whilst avoiding purely technical details, we hope to enable the reader to understand clearly the method of working, and the principles underlying the design of many of those instruments which are day by day becoming more and more necessary in modern life. Of course, what we shall give will be, after all, a mere outline, but we trust an interesting outline, of a subject which, in its full development, requires all the resources of mathematical and experimental science.

In the chapter on "conduction" we have partly anticipated the present chapter, by describing with sufficient detail the methods employed in measuring that property of matter known as electrical *resistance*. The other electrical quantities that it is most important to be able to measure accurately may be arranged under the following heads:—

(*a*) Quantity of Electricity.
(*b*) Electric Current.
(*c*) E.M.F. and P.D.
(*d*) Electric Power.
(*e*) Electric Energy.

These we propose to take in the above order, and although the list is far from being exhaustive, it is sufficiently extensive for our general plan.

(*a*).—Quantity of Electricity.

There are two practical methods by which quantities of electricity can be measured: one depending on the chemical effect which the given quantity of electricity will produce in a voltameter if passed through it, and the other depending upon the impulsive magnetic effect produced by the resulting current when the electricity is discharged through a galvanometer. The latter, which is, strictly speaking, a galvanometric method, belongs properly to, and will be described in, the next section.[1]

With regard to the voltameter method, we have a few pages back dealt very fully with the laws of electrolysis, and it only remains for us to describe the actual apparatus employed. As already remarked, this apparatus is extremely simple and, within certain limits, no great attention need be paid to actual dimensions. The best voltameter to use for exact work is undoubtedly the *silver voltameter*, one form of which, as arranged in the Central Institution, London, for the calibration of ampèremeters, is shown in Fig. 169. The voltameter part of the arrangement consists of a shallow and thin platinum dish, D, which contains a 25 per cent. solution of silver nitrate. This dish forms the kathode of the voltameter, and rests on three metal pins, which are in conducting-communication with the wire, W_2, when the copper spanner, B, is placed in the mercury cups, H H. The anode consists of a thick plate of silver, P, which is suspended in the solution by means of the strip, S, cut out of a sheet in one piece with P, and bent up at right angles. The plate, P, is wrapped in filter paper, to prevent any of the silver oxide which may be formed at the anode during electrolysis dropping into the platinum dish and thus

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[1] *Vide* page 359.

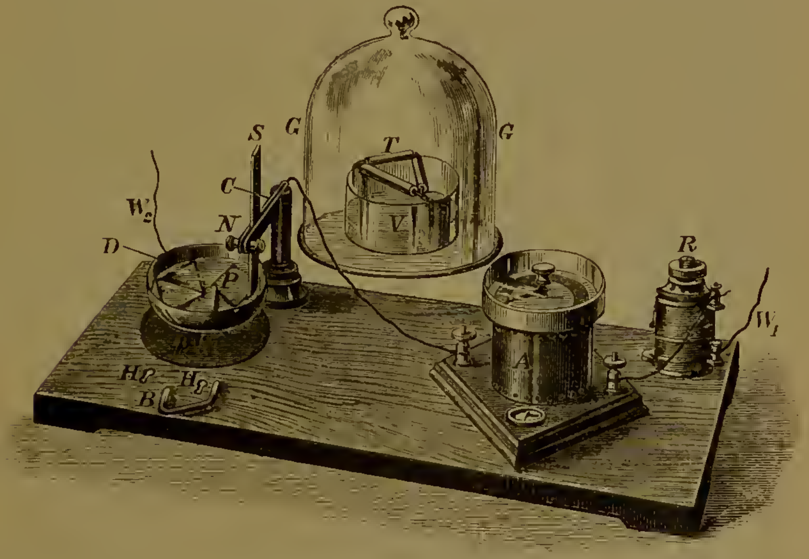

Fig. 169.—The Silver Voltameter.

increasing its weight. When the current passes from P to D through the silver nitrate, silver is dissolved off the anode, P, and enters the liquid as silver nitrate, whilst silver is deposited on the platinum kathode, P. The total quantity of electricity that passes from P to D can, therefore, be found by ascertaining the *increase of weight* of the platinum dish due to the silver deposited on it. It is found by experiment that the increase of weight of the kathode is more reliable than the loss of weight of the anode. Since we know that one coulomb deposits 0·001118 of a gramme of silver[1] we can find the total number of coulombs by dividing the increase of weight in grammes by this number, or

$$\left.\begin{array}{l}\text{Quantity in}\\ \textbf{Coulombs}\end{array}\right\} = \frac{\text{weight of Silver deposited }\textbf{(grammes)}.}{0\cdot001118}$$

To obtain accurate results several simple precautions are necessary. Both before and after the current has passed, the platinum dish, D, has to be cleaned, dried, and weighed. To get it quite clean it must be washed with distilled water, alcohol, and ether, then dried over a spirit lamp and left to cool in the sulphuric acid desiccator, G. In order that the deposit of silver may adhere so well to the platinum as not to be disturbed by the washing operations, the current must not exceed one ampère for every six square inches of kathode surface. If the current very much exceeds this, although the proper amount of silver will be separated at the kathode, it will not adhere well to it, and some may be lost whilst washing, thus leading to an inaccurate result.

The wires, W_1, W_2 (Fig. 169), are connected to a current generator, and the rest of the apparatus is inserted for the purpose of calibrating the ampèremeter (or ammeter), A. The current which passes through the voltameter also passes through A, and the adjustable resistance, R. If this current be kept *quite steady* we can deduce its value by a method to be described presently (page 334).

But it must not be forgotten, that whether the current be steady or not, providing it is never reversed, the voltameter will correctly measure the total quantity of electricity that passes through. It is, therefore, directly a measurer of quantity of electricity, and only indirectly a measurer of current.

Quantity of electricity may also be conveniently measured by means of a copper voltameter. This is easily arranged by placing two square copper plates vertically, about half-an-inch apart, in a solution of copper sulphate. In this test also the increase of weight of the kathode plate is used to estimate the quantity of electricity, and the precautions already described about cleansing and drying have to be observed. It will, therefore, be well to use *thin, hard* copper for the kathode, so that it may be as light as possible. With copper the current may be as great as one ampère to every two square inches of surface without getting a bad deposit. Of course in the final calculation the electro-chemical equivalent of copper (·000326) must be used instead of that of silver.

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[1] *Vide* Table VII., page 304.

An Electric Meter, based on the voltameter principle, was invented by Edison for the purpose of measuring the supply of electricity to private consumers; this will be described later in the chapter.

(*b*).—Measurement of Electric Current.

The problem of measuring the Electric Current with instruments adapted to the enormous range of magnitudes that are in common use has always been a fascinating one for scientists, and its solution has resulted in the production of some of the most beautiful instruments to be found in the whole realm of science. In their construction the resources, not only of electrical, but also of dynamical and optical, science have been laid under contribution, and we are now able to measure currents with a range of magnitude of more than one billion.

For the purpose of measuring a current, any one of its three effects may be employed, and it will be, therefore, best to treat separately the chemical, magnetic, and thermal methods of measurement; but of these by far the most important in practice is the magnetic method.

CHEMICAL METHODS.

The measurement of quantity of electricity by means of voltameters, which we have just described, can also be used for the measurement of electric currents, provided that the currents are *steady*, during the whole time that electrolysis is taking place. For the numerical value of the current is the *quantity of electricity* that flows *per second*; if, therefore, we know the *total quantity* that has passed through the voltameter, and the *time* during which the current continued, the quotient of the quantity divided by the time will be the *average value* of the current, and this will be the *actual value* if the current has been quite steady. To obtain this value in *ampères* the quantity must be measured in *coulombs* and the time in *seconds*, for

One Ampère = One Coulomb per second.

Thus, if the quantity of silver deposited in the voltameter in fifteen minutes show that 3,600 coulombs of electricity have passed, we find that the average current has been

$$= \frac{3{,}600 \textit{ coulombs}}{15 \times 60 \textit{ seconds}} = 4 \textit{ ampères}.$$

We have already referred in sufficient detail to the method of measuring the coulombs. To measure the time it is only necessary to have a good watch or chronometer, and to note the exact instant when the current is started in the voltameter, and again the exact instant when it is stopped. The interval between these two instants, expressed in seconds, is the time to be used in the calculation. As regards *steadiness*, the voltameter gives no visible indication at the time of any fluctuations in the current, and it is, therefore, necessary to place in the circuit an instrument such as a galvanometer, which will at once give notice of any change that the current may undergo. Voltameters as current measurers have, therefore, two serious drawbacks:

firstly, the method is tedious and requires a certain amount of experience and manipulative skill; and, secondly, they give no visible indication *at the time* of any change that may occur in the magnitude of the current—there is no indication of what the value of the current was at any given instant. Their advantages are that within certain limits the size and shape of the vessel, the size of the electrodes, the quantity and, to some extent, the constitution of the electrolyte are matters of indifference, and that no complicated mathematical calculation, involving delicate measurements of distances and dimensions, is required to interpret the results. Thus for ascertaining the value of, and for standardising the indications of, other instruments, subject to more complicated laws, they are invaluable.

Magnetic Methods.

As a means of detecting the existence of a current, of showing its fluctuations from moment to moment, and, finally, of measuring its absolute value when required, instruments whose indications depend upon the magnetic effect of the current, are much more convenient than those which depend upon either the chemical or thermal effects. The latter, with small currents at least, require time to develop heat to any sensible amount, whereas the change in the magnetic effect, consequent upon any change in the current, at once makes itself evident on the appliances used to detect it. The amount of chemical decomposition, or of heat, produced by a steady current is directly proportional to, and increases with, the time, whereas the magnetic field which it sets up is as great as soon as the current is established as it is hours, or even days, afterwards, provided the current be kept unchanged. Moreover, the strength of this magnetic field, if no iron be present, follows faithfully every change in the value of the current. It is, therefore, only necessary to devise some means of measuring this strength and of indicating its fluctuations for us to be able to measure the strength and the fluctuations of the current.

Instruments that are thus used for the purpose of measuring the magnitude of a current by means of its magnetic effect are called **galvanometers**, in honour of Galvani, to whom the science of current electricity owes so much. Essentially they must consist of two parts, (i.) a conductor to carry the current to be measured, and (ii.) some method of measuring the strength of the magnetic field which this current sets up at some previously-selected place in its neighbourhood.

The apparatus used by Oersted in the original experiment, by which he discovered the magnetic effect of the current, constitutes a rough and elementary form of galvanometer. A single straight conductor (Fig. 170), *a b*, is stretched over a pivoted magnetic needle, N S, and the supports turned round until the wire lies in the magnetic meridian, and, therefore, directly over the needle in its position of rest. If now an electric current be passed through the wire from *a* to *b* the needle will be deflected, and, according to the rules already given, will turn on its pivot in a clock-wise direction. But as soon as the needle moves out of the magnetic meridian, the earth's magnetic force tends to bring it back again to its original position. We, therefore, have two conflicting magnetic forces acting on the needle, (i.) the force of the magnetic field of the current, which tends to make the needle set east and west, and (ii.) the force of the earth's field, which tends to make it set north and south. Between these extremes the needle

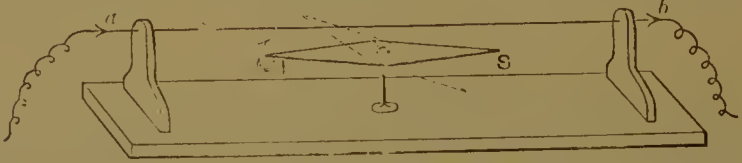

Fig. 170.—Oersted's Galvanoscope.

takes up some intermediate position, as indicated by the dotted lines; and since the deflecting force of the current depends upon its magnitude, it follows that the larger the current the further will the needle be deflected from its north-south position. By placing a graduated scale underneath the needle we would be able to read off its angular deflection. But the connection between this deflection and the magnitude of the current is by no means easy to deduce, although the arrangement is apparently a very simple one; and, therefore, the apparatus is a *galvanoscope*, or current *indicator*, rather than a *galvanometer*, or current *measurer*. All that it could do for us, if we wished to compare two currents by its aid, would be to indicate which was the larger current, for the larger current would give the greater deflection, provided we do not move any magnets in the neighbourhood during the two experiments.

Another defect of Oersted's galvanoscope is, that it will only give indications with fairly large currents; the field that would be set up by such currents as are ordinarily used in telegraphy would not move the needle perceptibly out of the meridian. On the other hand, the currents used in electric lighting would give large deflections; and this simple arrangement, made somewhat more compact, and with the field of a strong permanent magnet replacing the weak field of the earth, has been used for measuring currents of 1,000 ampères and upwards.

Galvanometers for Measuring Small Currents.

Notwithstanding this application, Oersted's apparatus remains far too *unsensitive*, as it is called, for indicating the existence of many of the currents used in ordinary electrical work. It is, therefore, important to examine in what ways its sensitiveness can be increased so that visible movements of the needle may be produced by very small currents. Now, we find, as we should expect, that the magnetic field of a current is stronger close to the conductor than at a distance and, therefore, our first step would be to bring the wire as near as possible to the needle. But this is not all: we have seen that when a wire is coiled up into a solenoid the magnetic field inside the solenoid becomes much stronger than that due to the straight current, even when there is only a single turn in the solenoid, and that the strength of the field increases with the number of turns. We are, therefore, not surprised to find that in one of the earliest attempts to increase the sensitiveness of the apparatus, the wire was made to pass many times round the needle, in the form of a kind of rectangular solenoid, as seen in Fig. 171.

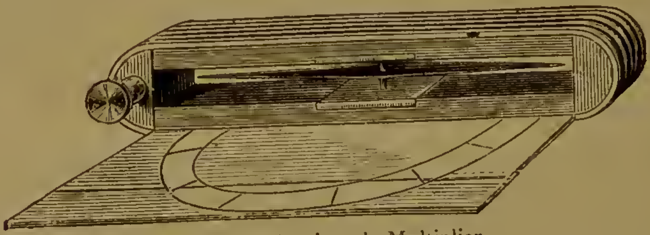

Fig. 171.—Schweigger's Multiplier.

This improvement is due to Schweigger, and is known as Schweigger's Multiplier, from the fact that each additional turn of wire approximately increases proportionately, or "multiplies," the sensitiveness of the instrument. For instance, with 100 turns the instrument will give approximately the same deflection with a small current as it will give with a current 100 times as great if it passes round only once. In Fig. 171 the pivots on which the needle turns are shown as working in the frame on which the coils are wound, and there is a circular scale underneath on which the position of the needle can be roughly observed.

But besides *increasing the strength of the field*, which tends to *deflect* the needle, we may also increase the sensitiveness of the instrument by *diminishing the controlling force*, which tends to bring the needle back to its position of rest. The most successful of the early attempts to increase the sensitiveness in this way was the device employed in the "Astatic Galvanometer." Instead of the one needle used in the earlier instruments, two, *n s* and *s′ n′* (Fig. 172), are employed. These are rigidly connected by the light rod, *a*, so as to be in the same plane, and one of them has its poles reversed with respect to the other; thus the north pole, *n*, of one is placed directly over the south pole, *s′*, of the other. If such a magnetic system be hung up by a light fibre of untwisted silk, one needle can only set north and south by compelling the other needle to set in a diametrically opposite position, *i.e.*, south and north. The two needles, therefore, tend to set in opposite directions, with the result that the stronger one overpowers the weaker, and points with its north pole towards the north, but the whole system

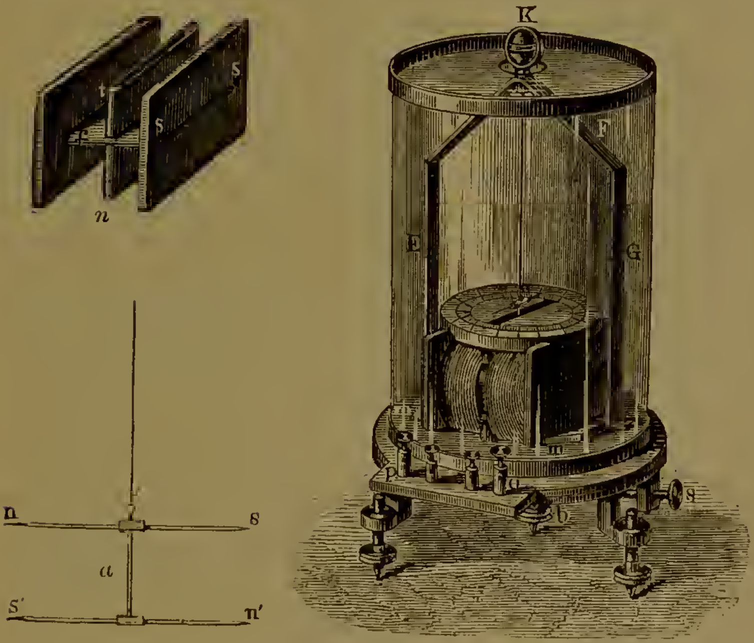

Fig. 172.—The Astatic Galvanometer.

is held in the magnetic meridian much less strongly than if the stronger needle were suspended alone. If the magnetic moments of the two magnets are exactly equal, they will exactly neutralise one another, and neither will be able to set itself in the magnetic meridian. In this state they are said to be "*Astatic*," and should point indifferently in any direction, but usually they will then set east and west, as it is well-nigh impossible to mount them so that their magnetic axes are in the same vertical plane. It is even seldom that a pair of magnets can be obtained of exactly equal moment, and, therefore, the needles of a so-called "Astatic Galvanometer" nearly always set north and south, though the difference between the moments of the two should be very slight.

The conductor that is to carry the current usually consists of silk-covered copper wire, and is wound upon the special frame shown separately at the left-hand top corner of the figure. The two central cross-pieces, *f* and *n*, of the framework are hollow, as can be seen at *t* and *s*, and after the coils are wound on in the manner shown in the complete instrument, the magnetic needles are lowered into the vertical slot until the lower one is free to move in the central horizontal slot. When in this position the upper needle is sufficiently high above the coils to allow the circular scale card to be placed below it. Thus the upper needle acts as an indicator to show how far the needles are deflected by the current. The zero of the scale is so placed that when pointing to it the needles lie parallel to the coils, and in using the instrument it should always be adjusted to this position before the current is passed through it.

In the instrument figured the conductor is wound on in two separate and similar coils, whose four ends are soldered to the four binding screws seen in front. This is so that the sensitiveness of the instrument may be altered by using either one coil or both coils connected in series. It can also be used *differentially* to measure the difference between two currents. To do this one current is sent through one coil and the other through the other, so as to tend to deflect the needle in the opposite direction; the resultant deflection will then depend approximately on the *difference* of the two currents.

It should be noticed that the advantage of using the nearly astatic needles is not confined to the fact that the earth's controlling effect is diminished, and, therefore, the deflection due to a particular current increased. In addition to this we find that *both* needles are deflected by the current in the *same direction.* For, suppose the current to be so passing round the coils that the lines of force *inside* run from east to west, then the lines *outside* must run from west to east. But the needle outside has its poles in the opposite direction to those of the needle inside, and, therefore, a west-to-east field will turn it in the same direction as an east-to-west field turns the inside needle. Thus, both needles act in the same way with regard to the deflecting current, but in opposite ways as regards the controlling field. On both accounts, therefore, the sensitiveness is increased.

As a minor, but not unimportant, improvement, it should be noticed that the needles, instead of working in pivots, are suspended by a long fibre of untwisted silk. This does not increase the sensitiveness of the instrument, but very materially reduces the mechanical friction, and thus enables the moving parts to set with greater certainty in the position of equilibrium due to the magnetic forces alone. The improvement is accompanied by the drawback that the instrument must be carefully *levelled* when used, and for this purpose it rests on three levelling screws, by which it can be adjusted.

It is interesting to notice in passing that the improvements in the galvanometer which we have been describing contributed very materially to the success of Melloni's brilliant experiments in radiant heat. Without an instrument capable of detecting much smaller currents than had previously been measured, those researches could not have been made. This is only one instance out of many that could be cited, where the improvement of instruments has led to important discoveries in unforeseen and, at first sight, apparently unconnected directions.

So far we have only considered electric and magnetic methods of increasing the sensitiveness of galvanometers by increasing the deflections produced by small currents. But it is obvious that having produced the greatest deflection which such methods permit, if we can then magnify the deflection by other means, we shall practically be able to detect still smaller currents, for deflections which would otherwise escape our notice will then become sensible. In the instrument just described, the deflection is read off by observing the movement of a pointer over the circumference of a circle a few inches in diameter. For very small deflections a low-power microscope might be used to detect any movement of the pointer, or the pointer itself might be lengthened so that its end should move over the circumference of a larger circle. Neither of these methods is very advantageous, though the first is the better. The second is open to the objection that the increase of length of the pointer necessarily adds to the mass and, therefore, to the sluggishness of the movable parts, and it, moreover, increases the bulk of the instrument by increasing the size of the fixed scale over which it moves. Weber pointed out the simplest solution of the difficulty by attaching a mirror to the movable magnets; the movements of this mirror could be observed by well-known optical methods. The device is, in reality, equivalent to employing a weightless beam of light as a pointer, instead of a more or less heavy wire, with the advantage that the beam may be many feet in length without affecting the movements of the needles at all. Wiedemann improved the apparatus by using a magnetised steel mirror as the suspended magnet. But the method was brought to its highest perfection by Lord Kelvin (then Sir William Thomson), who reduced the mass of the suspended system to a few grains by using a very light mirror and making the magnets of watch-spring steel. We owe many other minor improvements in the details of the instrument to the same indefatigable worker.

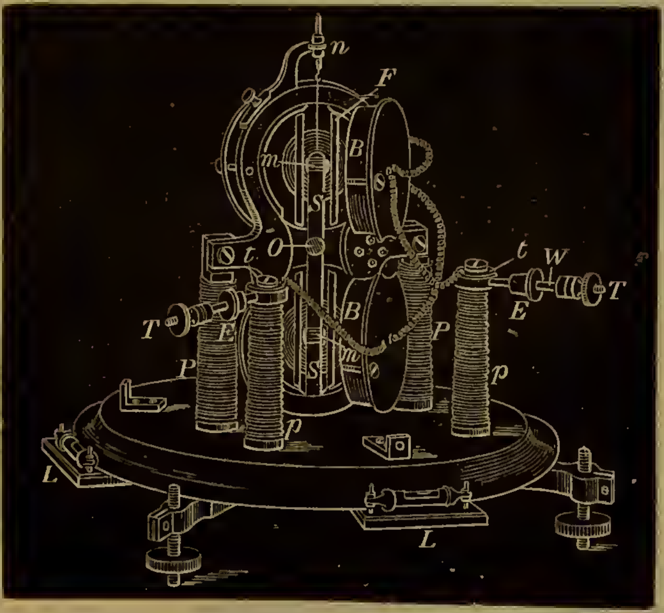

Fig. 173.—Lord Kelvin's Reflecting Galvanometer.

It will, we think, assist the reader to understand the principle of this improvement, if we first describe one of the modern forms of the Kelvin Reflecting Galvanometer. The coils, four in number, are contained in hollow boxes, two of which, B B (Fig. 173), are hinged to the other two so that they can be turned back as shown in the figure, in order that the suspended magnetic system may be placed in position or examined. When the instrument is in use these coils are closed up, face to face with the other two ;

the four coils then form electrically two coils only, and at the centre of each a very small system of magnets, *m m*, is suspended. The appearance of the coils when closed can be inferred from Fig. 179, which illustrates a slightly different form of the galvanometer. These two systems of magnets are mounted "astatically" (see Fig. 172) on a very light strip of mica, S S, to the centre of which is fixed a small and light concave mirror, O, and the whole is suspended by a fibre of quartz or of unspun silk to a hook on the arm *n*. The mass of the suspended magnetic system is thus reduced to a

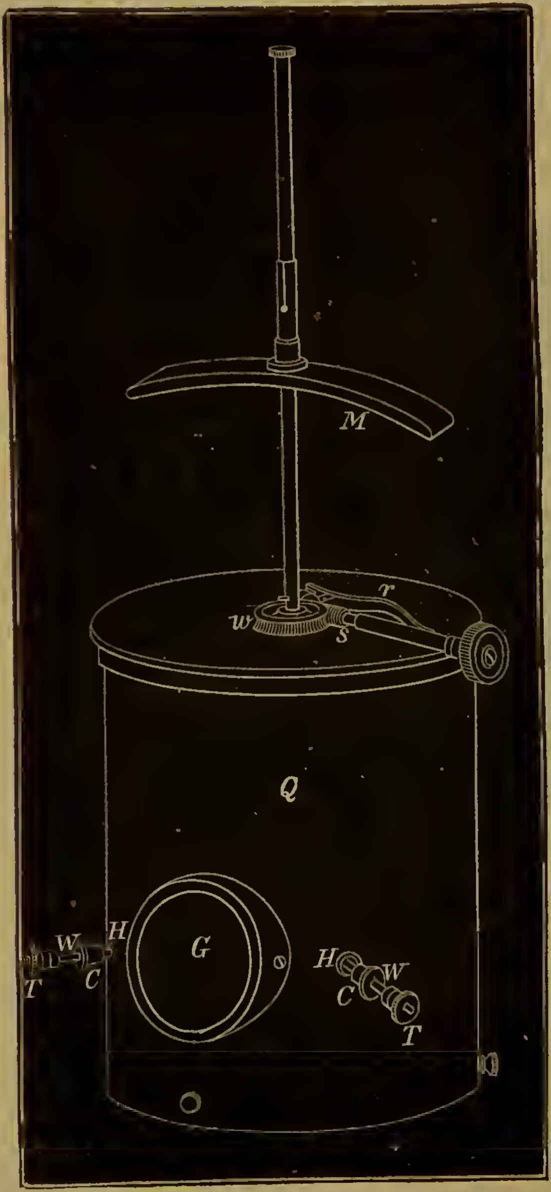

Fig. 174.--Outer Case of Reflecting Galvanometer.

minimum. The suspending hook is attached to a screw which, by means of the nut shown, can be moved up or down without twisting the fibre. The fixed coils are held in a framework which is supported by the corrugated ebonite pillars, P P, and thus very high insulation is obtained. The four coils are permanently joined up in series by the coiled wires that can be seen passing from one to the other, and the two ends of the conductor are brought to brass caps, *l l*, on the tops of the two other corrugated ebonite pillars, *p p*; from these caps stiff wires, W, pass through holes in the outer case, Q (Fig. 174), to the external terminals, T T. E E are ebonite plugs which slide on the wires, and are pushed into the holes, H H, of the outer case, to render it air- and dust-tight when not in use. In joining up the coils care must be taken that the currents in the different coils all tend to turn the magnets in the same direction. The principle to be followed is shown diagrammatically in Fig. 175, where the same letters are used as in Fig. 173, with the addition of *n s* and *s′ n′* for the two sets of magnets. The arrows show the direction of the current, which is opposite in the upper and lower coils. In the upper coils the lines of force due to the current will flow from front to back, past the magnets, *n s*, whereas in the lower coil they run from back

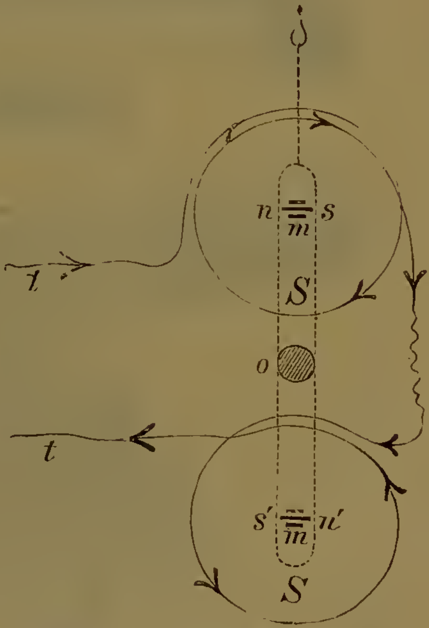

Fig. 175.—Connections of Upper and Lower Coils.

to front past $n' s'$. But the magnets are astatically reversed, and, therefore, the strip, S, to which they are attached, and with it the mirror, O, will be rotated in the same direction by the action on each set of magnets.

The cover, Q (Fig. 174), is of brass, but has a circular opening, G, covered with a flat piece of glass through which a beam of light can be directed on to the mirror, O. When the instrument is in use, the cover is fixed on to the base (Fig. 173), and the whole is levelled, by means of the levelling screws, with the aid of the two spirit levels, L L, which are set at right angles to one another, and so adjusted that when the bubbles of air are in the centres of the tubes,

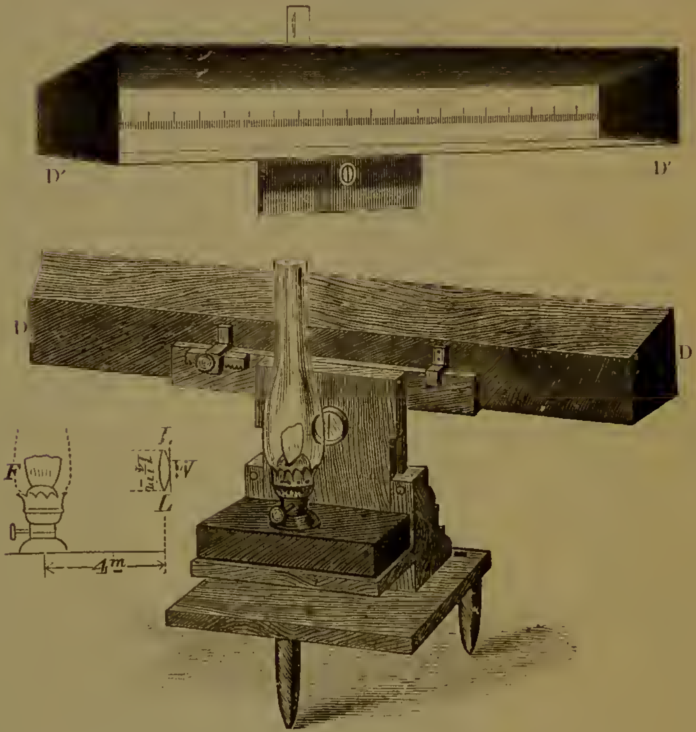

Fig. 176.—Lamp and Scale for Reflecting Galvanometer.

the strip, S S, hangs quite freely in the rather narrow space provided for it.

We are now in a position to explain the optical arrangements used to magnify the minute deflections of the strip, S S, and the mirror, O. A paraffin lamp, F (Fig. 176), is supported in the manner shown behind a double convex lens, L, of about four inches focal length. Above the lens is a scale, D D (the front of which is seen above at D′ D′), which is placed parallel to the opening, G (Fig. 174), in the galvanometer cover, and, therefore, directly facing the mirror, O (Fig. 173). The lens, L, is a little below, and the scale, D D, just as much above the level of the mirror; consequently light proceeding from the lens, L, is reflected on to the scale, D D.

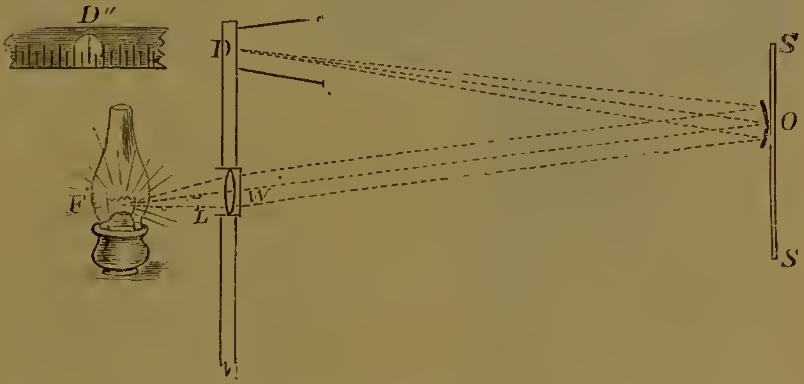

Fig. 177.—Mirror, Lamp, and Scale.

The course of the light is shown in Fig. 177. The lens, L, is placed at its focal distance from the lamp, and, therefore, the light falling upon it emerges as a beam of parallel light, L O, which falls upon the mirror, O, and is reflected to the scale, D. The scale is placed at a distance from the mirror equal to its focal length, and the parallel beam, L O, is reflected as a converging beam whose focus is at D. A bright image of the lens, L, is, therefore, formed at D, and if a vertical line be drawn on the lens or a vertical wire, W, placed immediately in front of it, an image of this line is seen crossing the bright disc of light. The appearance presented is shown at D″, which represents a short length of the scale with the bright circle crossed by the dark image of the wire. If now the mica slip, and with it the mirror, O, be turned round S S as an axis, the point, D, will move backwards and forwards along the scale and indicate the angular position of the mirror, O. As the distance O D may be six or eight feet, or even more if convenient, the magnification of the movement of O may be made very great. In connection with this magnification it is not unimportant to notice that, in accordance with a well-known law in optics, the reflected beam, O D, moves through an angle double of that through which the mirror, O, moves.

With such a delicate magnifying arrangement, excessively minute movements of the mirror can be detected and measured quite readily. In fact, so sensitive is the apparatus, that all mechanical disturbances have to be carefully eliminated. For instance, the most delicate instruments are placed on the top of massive piers of masonry, built up, where possible, from the solid rock ; or hung by indiarubber bands from an over-head beam. Even then, in a city like London, where the enormous traffic fills the apparently steady earth with all kinds of tremors, it is well-nigh impossible to obtain a steady spot of light during the busy hours of the day, and, in some instances, delicate researches have to be postponed until midnight and the small hours of the morning, when for a brief interval the great city is comparatively asleep, and the pulsing of its traffic dies down.

One drawback of the lamp and scale arrangement is that the room in which the experiments are made must be darkened. This difficulty is avoided on the Continent by using a telescope and a plane mirror instead of a lamp and a concave mirror, but the method is much more fatiguing to the observer, who has to keep his eye fixed at the eye-piece of the telescope. Another method, which combines all the advantages of the lamp and scale without requiring a darkened room, is now being very generally adopted. It consists in replacing the opaque scale of Fig. 176 by a transparent scale, behind which the observer stands. One method of arranging such a scale is shown in Fig. 178. The source of light is a glow-lamp in the box, B, to which current is supplied by the terminals, T T. The light is directed through a lens in the tube, L, to the mirror of the galvanometer or other instrument, by which it is reflected back on the scale, S, on which it is brought to a focus. S is a semi-transparent scale of ground glass, and the observer, standing behind it, can see the spot of light plainly without the room being darkened.

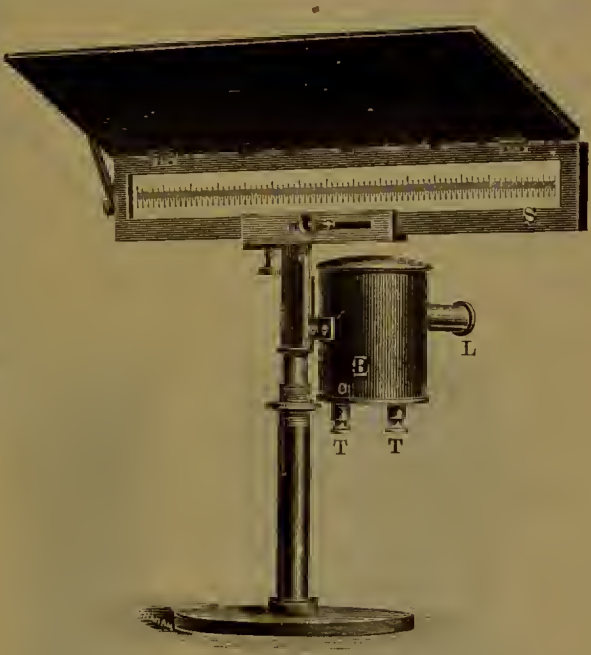

Fig. 178.—Lamp Stand, with Transparent Scale and Glow Lamp.

There is still another and independent way in which the sensitiveness of the instruments we have been describing can be easily increased or diminished within certain limits. Hitherto we have spoken of the movable magnet as being placed in, and controlled by, the magnetic field of the earth.

But it is obvious that any other magnetic field would serve the purpose of a controlling field, and if this artificial field were weaker than that of the earth, a greater deflection would be produced by a given current, since the forces tending to keep the needle at zero would be smaller. On the other hand, if the artificial field were stronger, the deflection would be lessened. Accordingly there is usually attached to the case of a sensitive galvanometer a movable permanent magnet, M (Figs. 174 and 179), which can be slid up and down the rod on which it is placed, thus producing a weaker or stronger field at the suspended magnets inside. Another use of this magnet is to adjust the spot of light to zero when no current is passing. By turning the screw, S, the vertical rod, and with it the

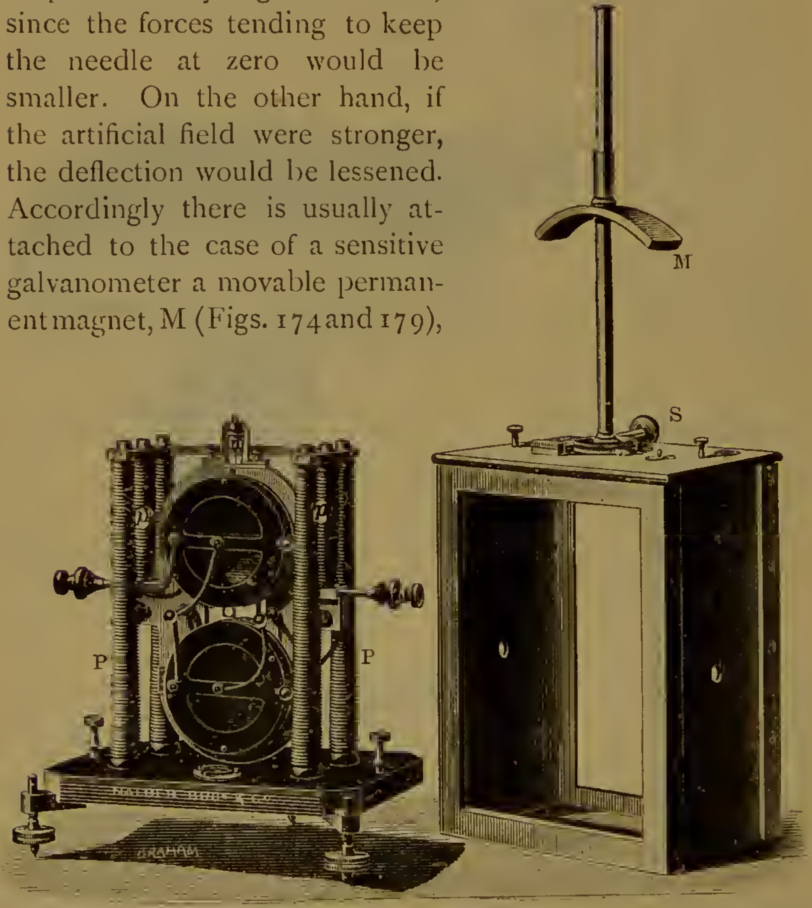

Fig. 179.—Sensitive Reflecting Galvanometer.

fixed magnet, M, is rotated, and the direction of the controlling field and the set of the suspended magnets altered.

For reasons upon which we need not dwell in detail it would seem better, with astatic galvanometers, to place this controlling permanent magnet in the horizontal plane passing through the centre of the suspended astatic system. Some galvanometers recently constructed have the magnet placed in this plane and movable in it (*see* Fig. 187).

In Fig. 179 we illustrate what is probably the most sensitive instrument of this class hitherto constructed. It was made two or three years ago by Messrs. Nalder Brothers for the City Guilds' Central Institution. To secure exceptionally high insulation, the framework which holds the coils is suspended from the four outermost long ebonite pillars, P P, and the terminals are attached to the two shorter pillars, *p p*. The copper conductor is a very fine thread, only 0·0014 inch in diameter, and is 85,400 feet, or over sixteen miles, long; it is wound on in a great number of turns, and has a resistance of 355,000 ohms. With this instrument a current of one thirty-sixth thousandth part of a millionth of an ampère can be detected.

In all the instruments yet referred to, the coils carrying the current to be measured have been fixed, and the magnets acted upon have been movable. What we are chiefly concerned with, however, is the *relative* motions of the two systems, and in the foregoing cases the magnets were left free to move because they were less massive than the coils, and, therefore, were more easily moved by the mechanical forces brought into play than the coils would have been, had the latter been movable and the magnets fixed. But Clerk-Maxwell has shown[1] that a light suspended coil placed in a strong magnetic field may be used as a galvanometer. In Fig. 180, reproduced from Clerk-Maxwell's great work, the coil is suspended by means of the two wires, A and B, by which the current enters and leaves. It is placed between the poles, N S, of a powerful magnet, which may either be an electro-magnet or a permanent one, but in practice is usually the latter. To concentrate the magnetic field on the vertical sides of the coil, the soft iron piece, D, is placed between the poles. When the current passes through the coil, the latter tends to set with its plane at right angles to the field of the large magnet, so that its lines of force may coincide with those of the magnet. It is prevented from taking up this position by the torsion which would thereby be placed on the wires A and B. Consequently an intermediate position will be taken up, and the deflection read in any of the ways already described may be used as a measure of the current strength.

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[1] *Electricity and Magnetism*, Vol. II., par. 721.

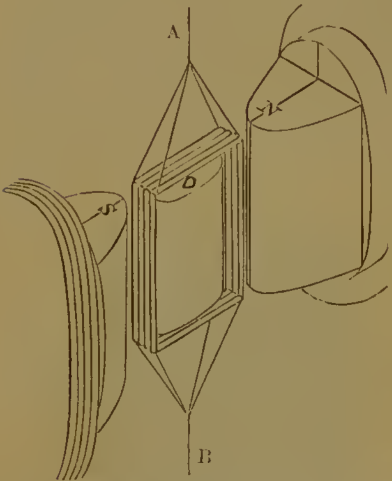

Fig. 180.—Maxwell's Suspended Coil Galvanometer.

The idea thus thrown out has been embodied by M. D'Arsonval in a practical instrument for measuring small currents. A permanent and powerful horseshoe magnet, M M (Fig. 181), is fixed with its poles upward on a base board, B, provided with the usual levelling screws, S S. Between the poles is a cylinder, A, of soft iron fixed firmly to the upright vertical rod, R; this cylinder concentrates the lines of force of the magnet in the narrow gaps between it and the magnet poles. In these narrow gaps the coil, *c c*, is suspended between the *wires*, *a* and *b*, to which its ends are electrically connected, the wires being kept taut by the adjustable spring, *s*. The mirror, *m*, is mounted at the top of the coil, and moves with it. The terminals, *t t'*, are placed outside the cover, Q, one of them being connected to the upper wire, *a*, through the rod, R, and the other to the lower wire, *b*, through the spring, *s*. If now a current be sent through the coil, *c c*, from *t* to *t'*, the coil and with it the mirror, *m*, will tend to move, as already explained, into a position at right angles to the lines of force of M M. But in so moving it will twist the wires, *a* and *b*, and this twist will tend to bring it back to the position of rest; it will, therefore, take up some intermediate position which may be observed with a beam of light directed on the mirror in the manner already described (pp. 347 to 349). The greater the current the greater will be the deflection, but the deflections are not necessarily proportional to the currents.

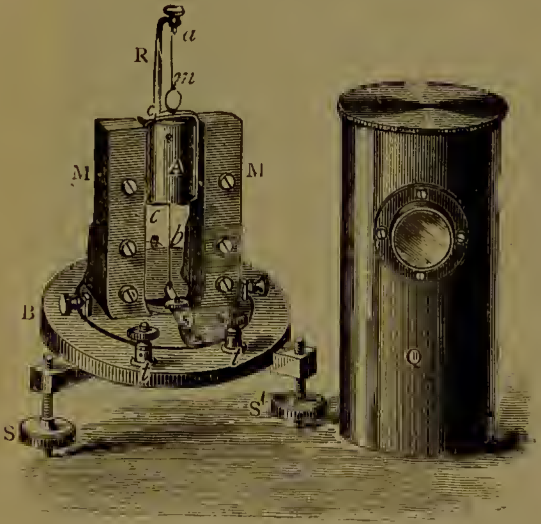

Fig. 181.—D'Arsonval's (Maxwell) Galvanometer.

Shunting Galvanometers.—The range of currents that any particular galvanometer can directly measure is necessarily limited; on the one side we may have currents so small as not to produce an appreciable movement, and on the other side currents so large that they cause the pointer to strike against the stops, or in a reflecting galvanometer make the spot of light move right off the scale.

We have endeavoured to describe some of the refinements by which the first class of currents may be reached and measured. Fortunately the second class, *i.e.*, the currents which are too large, may frequently be brought within the range of the instrument by a very simple electrical device known as *shunting*. By Ohm's law we know that if a current has a choice of two paths it will divide itself between them inversely as their resistances, the smaller resistance receiving the larger current, and *vice versâ*. If, therefore, a current is too large for a particular galvanometer, all we have to do is to provide a bye-pass or *shunt* for part of it, and only take a current of convenient magnitude through the galvanometer. Thus if *g* and *g′* (Fig. 182) be the terminals of a galvanometer, G; *w w′*, the wires connecting it with the rest of the circuit, and if we place a coil, *s*, across the terminals, *g g′*; the current coming along *w* divides at *g* into two parts, one of which flows through the galvanometer, G, and is measured, and the other through the shunt coil, *s*; these currents unite again at *g′* and pass on along *w′*. The fraction of the current in *w*, which passes through G, will be known if we know the relative resistances of G and *s*. For instance, suppose the resistance of *s* is $\frac{1}{99}$th of the resistance of G, then we know that ninety-nine parts of the current will pass through *s* for every part which passes through G; G thus only receives $\frac{1}{100}$th part of the current in *w*, which is, therefore, 100 times the current measured by the galvanometer. For convenience special boxes of resistances, called *shunt boxes*, are supplied with

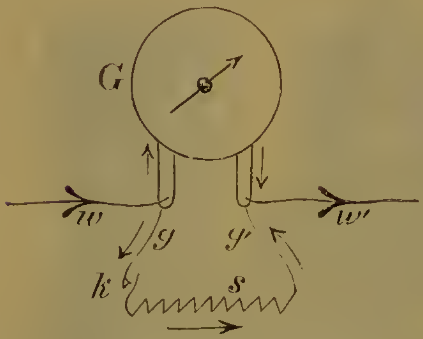

Fig. 182.—Shunting a Galvanometer.

sensitive galvanometers, each resistance being a definite fraction of the resistance of the galvanometer. The fractions usually chosen are $\frac{1}{9}$, $\frac{1}{99}$, $\frac{1}{999}$, so that the full current is 10, 100, or 1,000 times the current measured by the galvanometer. One of these shunt boxes for very sensitive galvanometers, is illustrated in Fig. 183. This box contains three coils to be used as shunts; one end of each coil is connected to the brass block, C, the other ends being connected to D, E, and F respectively. A B is a continuous brass block, which can be joined to either D, E, or F by inserting the plug, *cc*, in the appropriate hole; S and S′ are the terminals which are attached to the galvanometer terminals. When the plug is placed as shown in the figure the current arriving at S divides between the galvanometer and the coil, C D; this coil having $\frac{1}{9}$th of the resistance of the galvanometer, the current measured by the latter must be multiplied by ten to give the full current before shunting. To secure good insulation the various brass blocks are mounted on ebonite pillars, P P ...; the handle,

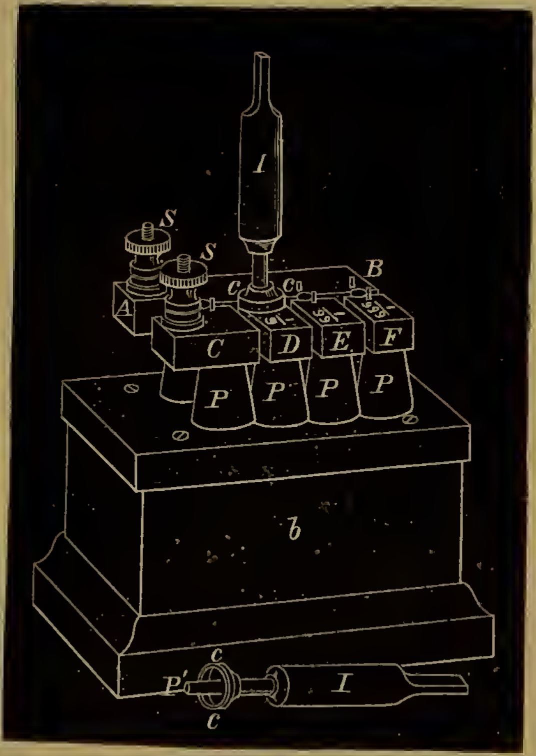

Fig. 183.—Shunt Box for Sensitive Galvanometer.

I, of the plug is also of ebonite, so that the experimenter may not make electrical contact with the circuit in moving the plug from one hole to another. A hole is provided by which the blocks, A and C, can be connected; when the plug is in this hole the galvanometer is said to be *short-circuited*, for practically no current goes through the instrument, however great the current from S to S′ may be. Thus by always leaving the plug in this hole when the galvanometer is not in use, it is protected from being damaged by a current being accidentally sent through it.

Simple Sensitive Galvanometers.—The modern instruments described above are chiefly examples of the further developments in their particular directions to which the art of constructing delicate apparatus has been carried; consequently they are usually expensive, as much skilled labour, and special knowledge in connection with many minor details, are required in their construction. Moreover, for many ordinary purposes, the degree of elaboration attained is not required, and a more easily constructed instrument, combining simplicity with a fair amount of accuracy, is all that is needed. We shall, therefore, conclude this section by describing two instruments which we believe fulfil these conditions; the first, a reflecting galvanometer, requiring, therefore, a lamp and scale for its use; the other, a direct-reading instrument, with ordinary pointer and circular scale.

The simple reflecting galvanometer (Fig. 184), designed by Mr. Mather, consists of two coils, C and C′, resting, with a narrow space between them, in a suitably-shaped open box. The ends of the coils are brought to screws on a narrow block in front of the box, and these screws are connected to the two terminals placed outside the simple glass shade which shields the coils and mirror from air currents and dust. A thin strip of mica, S S, hangs in the narrow slot between the coils and carries the mirror, M, and three sets of magnets, m_1, m_2, m_3; of these, m_2 hangs at the centre of the coils, and m_1 and m_3 just outside the circumference. The magnets, m_1 and m_3, have their poles turned in the opposite direction to those of m_2, and the whole forms a nearly astatic system. The strip of mica is hung by a fibre of unspun silk from a simple support, P, where there is an arrangement for raising and lowering it. The usual levelling screws are provided, but the controlling magnet, if required, must be supported independently in any convenient spot near the instrument. With this galvanometer many of the experiments, for which more expensive instruments are frequently used, can be performed with a high degree of accuracy. Another special advantage of the design is that the coils, C and C′, can be removed, and other coils giving greater or less sensitiveness placed in position in a few minutes. A great range can thus be obtained without much additional expense.

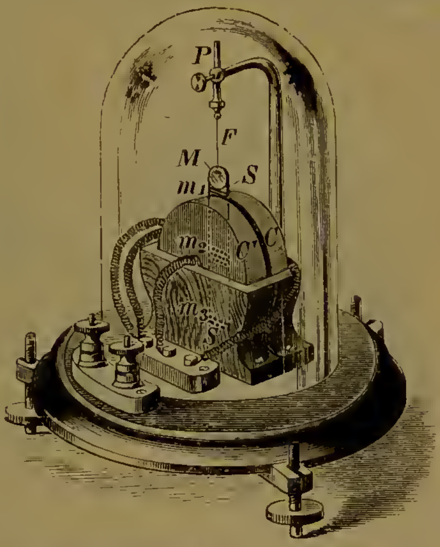

Fig. 184—Mather's Reflecting Galvanometer.

One drawback of most sensitive instruments with a pointer and scale is that the deflections are not proportional to the current. For instance, with the astatic galvanometer of Fig. 172, the current that produces a deflection of, say, 36° is much more than double the current required to give a deflection of 18°. If, therefore, it is required to compare two currents with such an instrument, experiments must be made beforehand to determine the relative values of the currents that produce the various deflections. Such a process is called *calibrating* the galvanometer; the results are recorded for reference, but their use involves a certain amount of trouble and liability to error. To avoid this the instrument shown in Fig. 185 has been designed; it has the advantage that up to, or a little beyond, 45° the deflections are proportional to the currents. Thus the current required to produce a deflection of 30° is three times the current required for a deflection of 10°, and similarly for other deflections up to the limit named. The arrangement of the parts is shown in Fig. 186; the coils, C C, are wound upon two semi-circular or D-shaped blocks, and are placed horizontally opposite one another at a distance apart a little less than the length of the magnetic needle, *n s*. The needle is suspended by a silk fibre from a simple support, and has attached to it a long light pointer, *p p*, the end of which moves over a circular card graduated in ordinary degrees. The needle is higher than the coils, so that the pointer swings clear of them. In Fig. 185 the coils are hidden by a thin sheet of looking-glass placed between them and the needle, to enable the deflection to be read with greater accuracy. Greater sensitiveness at a slightly additional cost can be obtained by using an "astatic pair" of needles, as in Fig. 172; the upper needle should be in the position of *n s*, Fig. 186, and the lower one in a symmetrical position *below* the coils. For the proportional law to hold true the controlling field must be *uniform*: the best field is that due to the earth alone, but if a controlling

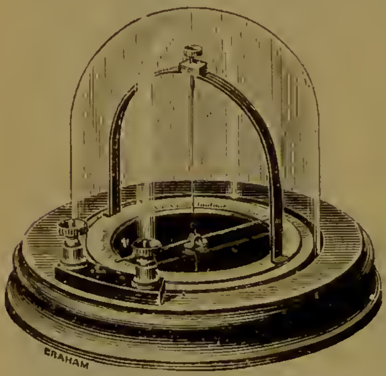

Fig. 185.—Proportional Galvanometer.

magnet is used it must not be placed very close to the galvanometer.

Ballistic Galvanometers.—Besides measuring currents, galvanometers can also be used to measure quantities of electricity as already mentioned in the last section. Of course, for a steady current the quantity of electricity that has passed through the instrument can always be obtained by multiplying the current by the time of flow, but we are referring now to the measurement of charges of electricity accumulated on conductors—as, for instance, the charge of a submarine cable, or of a condenser or a Leyden jar. If such a conductor be discharged through a sufficiently sensitive galvanometer there will be no permanent deflection because the current is only momentary, but there will be an impulsive movement of the needle, which will then return to rest at its former zero. It can be shown mathematically that, provided the whole discharge has passed through before the needle has sensibly moved, the limit of the *first* swing of the needle is a measure of the quantity of electricity that has passed. This quantity is, in fact, proportional to

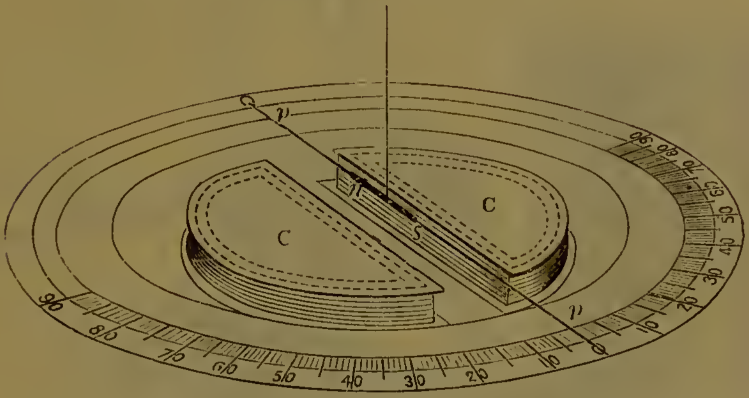

Fig. 186.—Principle of Proportional Galvanometer.

the sine of half the angle of this first swing, or, in symbols—

$$\text{Quantity discharged, } \propto \text{Sin } \frac{S}{2},$$

where S is the angular value of the first swing.

Most sensitive reflecting galvanometers may be used for making this measurement, but one built specially for the purpose is better, and is known as a *ballistic* galvanometer.

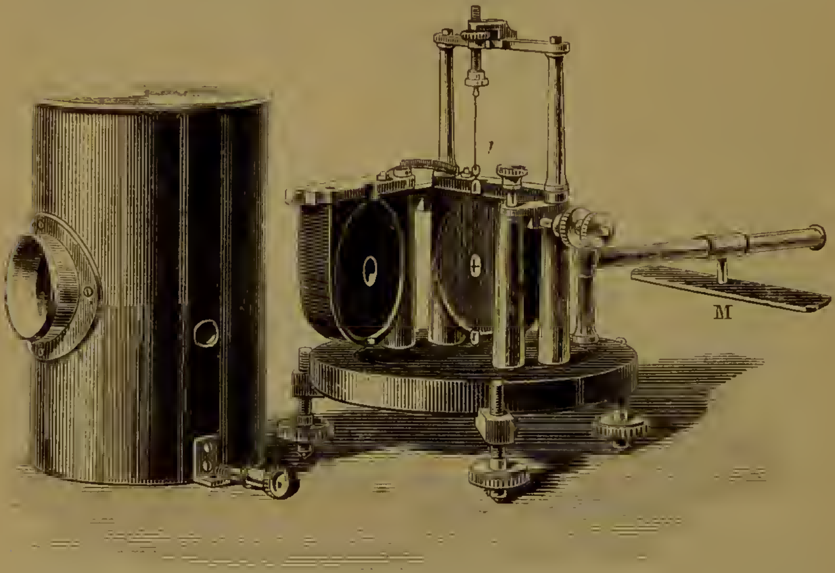

Fig. 187.—Nalder's Ballistic Galvanometer.

The particular modifications required are directed to reducing to a minimum all sources of kinetic and magnetic friction, which tend to retard the motion of the needle, though they might not affect its steady deflection. Such an instrument, designed by Messrs. Nalder Brothers, is shown in Fig. 187. The coils, one of which is swung back to show the suspended magnets, are in ebonite cases, and all metal mountings are removed from the neighbourhood of the magnets. There are four of these magnets, suspended in the usual way, two at the centre and one each at the top and bottom of the coils. They form an astatic system, and to reduce the air friction, when they revolve, to a minimum, they have externally the form of cylinders whose axes are in the axis of suspension. Such a system when once set swinging encounters very little friction, and will swing for a long time before coming to rest. It is, therefore, well adapted to measure the impulse given by a sudden discharge through the coils, for the needle will reach the end of the first swing without having lost by friction much of the energy imparted to it. The mirror, *l*, also is made very small, so as not to disturb the air much when moving. The controlling magnet, M, is placed where it ought to be, on a level with the centre of the astatic system, instead of in the usual position above.

A Ballistic Galvanometer should be used for the measurement of permeability described on page 325, for the accuracy of the measurement depends upon the correct estimation of the quantity of electricity set in motion by magneto-electric induction.

Galvanometers for Measuring Large Currents.

The enormous development during the last ten or twelve years of electric lighting, and the use of large currents of electricity for other purposes, has created a demand for accurate galvanometers specially adapted for the measurement of such currents. Some of the difficulties met with in constructing sensitive galvanometers are eliminated by the change of conditions. For instance, the magnetic fields set up by large currents are stronger than those due to small currents, and, therefore, the mechanical forces that may be called into play by them, though still small, are not so excessively minute as to require the most delicate refinements of a Physical Laboratory to detect and measure them. The efforts of constructors have, therefore, been directed to other points, amongst which the chief has been to produce an instrument entirely self-contained, whose indications shall not change from day to day or from year to year, and shall not be affected by the magnetic fields met with in rooms where dynamos are working, or in the neighbourhood of large currents. Also, as the instruments have to be used by workmen untrained in the intricacies of electrical science, they must directly indicate at a glance the number of ampères passing through, just as a good clock shows the time of day, or a thermometer the temperature of the room in which it is placed. They must also not be damaged by somewhat rough usage. For convenience galvanometers for measuring large currents are usually referred to as *Ampèremeters*, or more briefly, **Ammeters.** Of those in use we can only describe one or two.

In most of the sensitive instruments that we have described, the controlling force tending to bring the needle back to zero has been the magnetic action of a field set up by the earth, or some external and usually weak magnet. For our present purpose such a method of control would obviously be useless, as the controlling force would vary enormously if the instrument were placed near dynamos or large and varying electric currents. In many instruments, therefore, a mechanical force, such as that of gravity or of a coiled spring, is used to bring the movable part of the instrument to its zero position. Where magnetic controls are used, the magnetic field must be a part of the instrument and very powerful, so as not to be appreciably disturbed by the external influences to which we have alluded.

One of the earliest instruments to fulfil the specified conditions in a fairly satisfactory manner was the Permanent Magnet Ammeter of Professors Ayrton and Perry, by whom the name Ammeter was first used. An external view of one form of the instrument is given in Fig. 188, and the essential details of construction are shown in Fig. 189. The controlling field is that set up by the powerful permanent steel magnet, M M, in the narrow gap between the soft iron pole-pieces, P P. The needle is contained in the brass tube, which is mounted between the poles; it consists of a little oblong piece of soft iron with rounded ends, and is fixed to the same spindle that carries the long aluminium pointer which serves as an indicator of its position. The needle itself is not shown in Fig. 189, being hidden by the tube. The spindle is mounted in jewelled centres, so that the

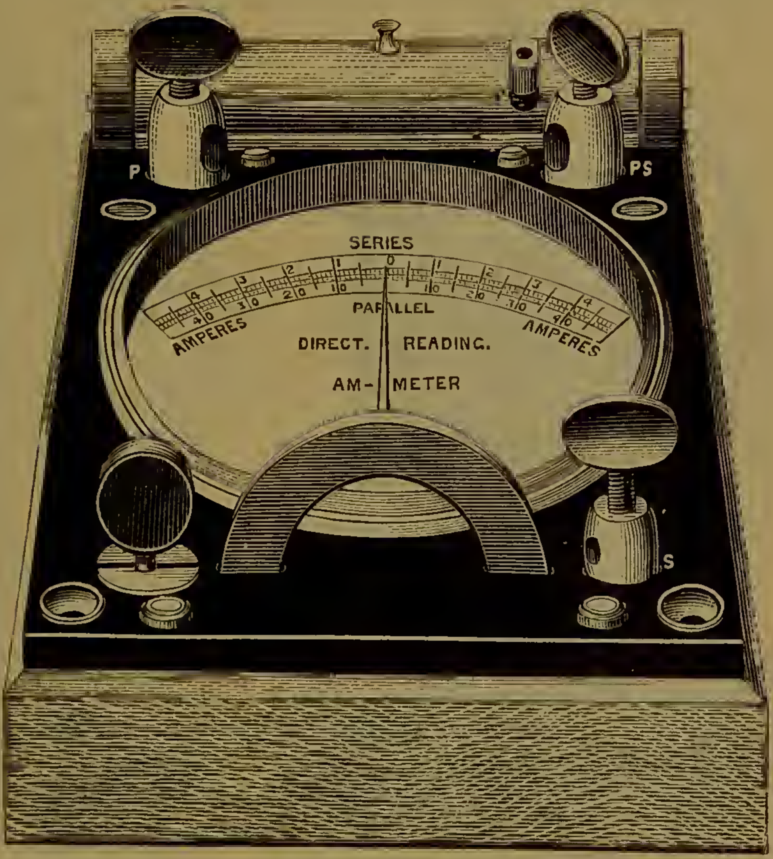

Fig. 188.—Direct Reading Ammeter.

needle and pointer move with very little friction. A A is a brass tube which forms the core of the coil, and on which it is wound. When a current is passed through this coil, its internal lines of force flow parallel to the axis of A A, and, therefore, at right angles to the lines of force between the poles, P P. Thus the little soft iron needle takes up some position intermediate between these two directions, and the greater the current the greater the deflection. By properly proportioning the different parts of the instrument the deflections can be made proportional to the current up to 45° degrees or more. F F are soft iron cores that can be screwed into, or out of, A A, to assist in adjusting the instrument, and the additional parts seen in Fig. 188 are for purposes of adjustment and calibration, to which we need not refer.

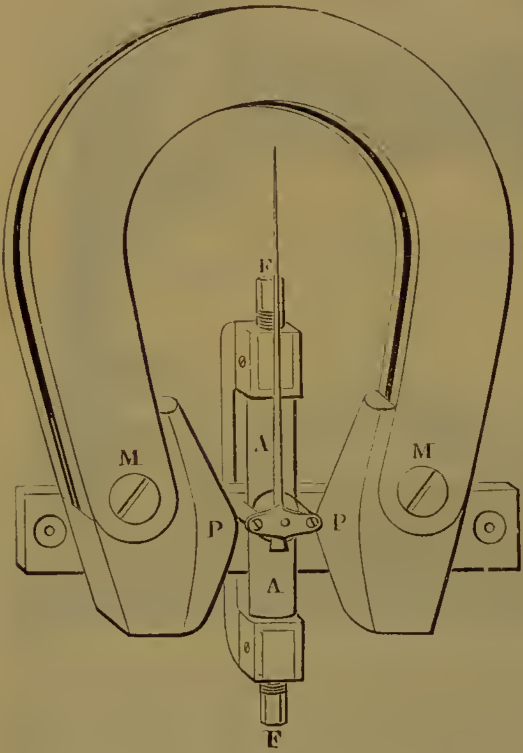

Fig. 189.—Principle of Direct Reading Ammeter.

In other instruments in which magnetic controlling fields are used, the permanent steel magnet is replaced by an electro-magnet, which is excited either by the whole or by a part of the current passing through the instrument. The ampère-meters of Messrs. Crompton and Kapp, and some of Messrs. Paterson and Cooper's instruments, belong to this class. The general principle will be understood from our description of the permanent magnet ammeter; it would lead us too far into technical details if we attempted to discuss the relative advantages and disadvantages of the two methods.

We turn now to instruments in which the mechanical effect of the magnetic action of the current is counterbalanced and measured by ordinary mechanical and non-magnetic forces.

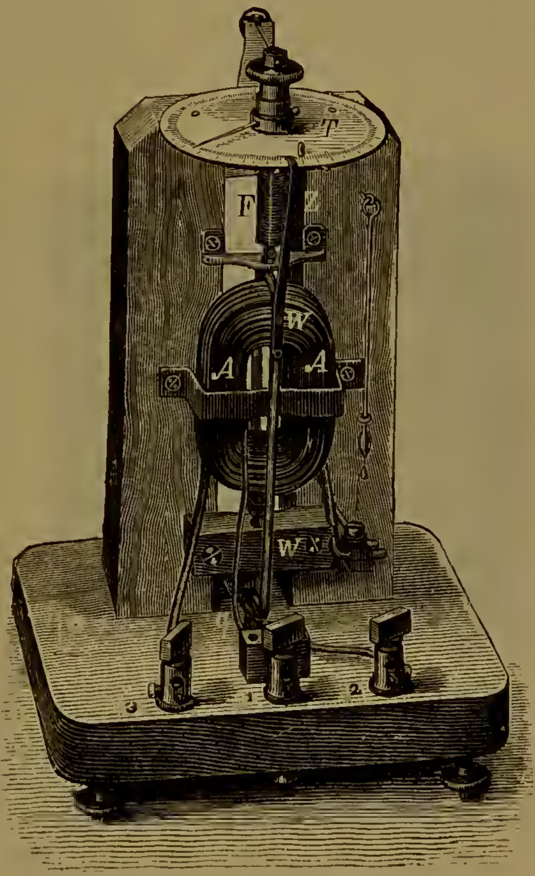

Fig. 190.—Siemens' Electro-Dynamometer

The **Siemens' Electro-Dynamometer,** which was the first widely-used instrument to employ a mechanical method of control, is shown in Fig. 190. The conductor carrying the current is partly fixed and partly movable. The current is first led from the binding-screw, 3, through a fixed coil, A A, mounted with its plane vertical as shown; it then passes to a mercury cup contained in the block immediately below the coil. Into this mercury cup there freely dips one end of the movable coil, W W, which usually consists of a single turn of stout copper wire, the other end of which hangs freely in a mercury cup, *q*, in the base of the instrument; this mercury cup is connected to the binding screw 1, from which the current is led away to the other parts of the circuit. The course of the current will, perhaps, be better understood by reference to Fig. 191, in which the fixed coil is diagrammatically represented by a single loop, A B C D, one end of which is attached to a binding screw and the other to the outside of the mercury cup, *m*. The moveable coil, E F G, has its ends dipping into the two mercury cups, *m* and *m′*, and the latter (*m′*) is directly connected to the other binding-screw. The two coils are thus electrically joined *in series*, and the same current passes through each. Now the mechanical force between two current-carrying coils is, *cæteris paribus*, proportional to the current in each, and is, therefore, proportional to the product of the two currents. Thus, where the two currents are the same, the force must be proportional to the *product of the current by itself*, or, as it is usually called, to the *square of the current*.

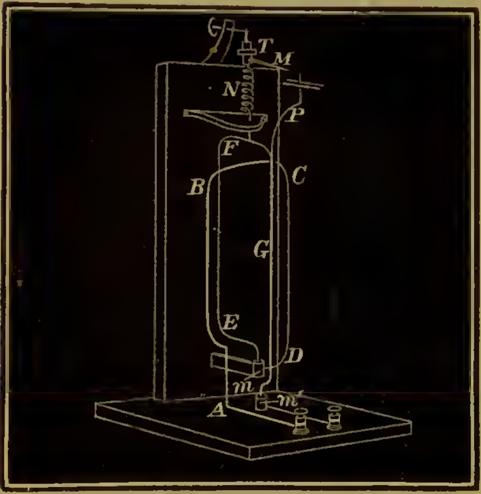

Fig. 191.—Principle of Siemens' Electro-Dynamometer.

The weight of the movable coil is supported by a silk thread attached to the upper part of the instrument, and there is also attached to the coil the lower end of a long and closely-coiled spiral spring, N (Fig. 191); the upper end of this spring is made fast to the spindle, T, that carries the indicator, M. A pointer, P, attached to the coil shows its position on the graduated circle. It will be noticed that when the movable coil is in the position shown in the figure, it is at right angles to the fixed coil, and the action between the magnetic fields of the coils is such as to tend to drag the movable coil into the plane of the fixed coil, so that their fields shall coincide. The relative directions of the two currents are so arranged that this has to be so accomplished by a counter-clockwise rotation of the coil, W, or a movement of the pointer, P, to the right. If now the spindle, T, be turned in a clockwise direction, the spiral spring drags the coil and its pointer, P, to the left with a force proportional to the angle turned through. There is, therefore, for each current, some position of the indicator, M, where the mechanical drag of the spring to the left exactly balances the drag of the two magnetic fields to the right, and the pointer, P, stands at zero. When this is the case, the reading of M measures the current passing.

From what we have said, it will be seen that the angle through which M is turned is proportional to the square of the current, or, in other words, the *current is proportional to the square root of the angle*, when P stands at zero. This square root multiplied by some constant will give the current in ampères. The constant for each instrument has to be ascertained by direct experiment.

The Siemens' Electro-Dynamometer may be taken as a type of a large number of instruments known as *zero instruments*. In all these the tendency of the movable part to move when the current passes is counteracted by some adjustment, and the indicator of the movable part is brought back to zero before a reading is taken. The amount of the adjustment necessary is then taken as the reading of the instrument. The necessity for such an adjustment is obviously a disadvantage if the current be not perfectly steady.

Ayrton and Perry's Magnifying Spring Ammeter is a widely-used instrument, in which the controlling

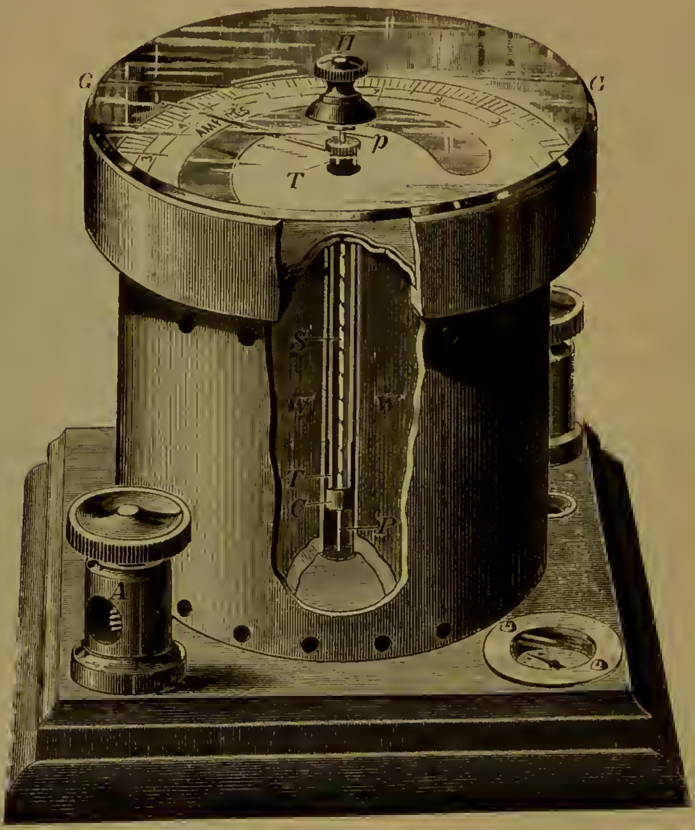

Fig. 192.—Ayrton and Perry's Magnifying Spring Ammeter.

force is that due to the axial stretching of a coiled spiral spring, and the amount of the stretching is magnified by the spring itself, which is ingeniously constructed for this purpose. The magnetic principle employed is that already referred to and illustrated on page 166, namely, that a soft iron rod placed unsymmetrically on the axis of a solenoid is drawn into the solenoid when the current passes. The construction of the instrument is shown in Fig. 192. The space, W W, is filled with the horizontal coils of a solenoid whose axis is vertical. T T is a thin tube of very soft iron, the upper end of which is outside the solenoid, and carries a cap and pointer; this cap slides freely on the spindle, *p*, which is fixed to the glass top of the instrument. The lower end of T T is attached to the cap, C, which carries the lower spindle, P, the latter being free to move up and down in a hole in the base of the instrument. The iron tube, with its accessories, is hung from the lower end of a long, thin, spiral spring, S, made of hard phosphor-bronze, which passes down through the axis of the tube. The upper end of the spring is made fast to the spindle, *p*.

The spring itself is of a peculiar construction, which will be better understood by reference to Fig. 193, in which a few turns of it are shown on a larger scale. It is somewhat like a closely-coiled wood shaving, and has this peculiar property—that if one end be fixed and the other end be slightly drawn out in the direction of the axis, this free end will *turn through a large angle for a very small extension.*

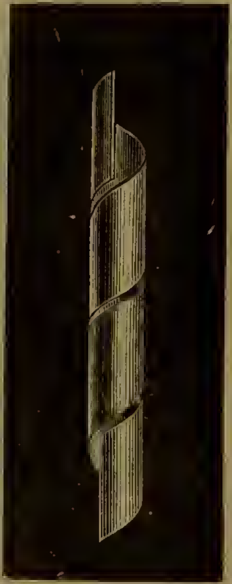

Fig. 193.—Ayrton and Perry's Magnifying Spring.

The action of the instrument will now be readily understood. When the current passes, the solenoid sucks in the soft iron tube, T T; in doing this it extends the spiral spring, S, whose lower end is attached to the tube. But this extension of the spring causes its lower end, and with it the iron tube, to rotate through an angle which is very large for a small extension, and the amount of the rotation is indicated by the pointer on the dial.

The dial, instead of being marked with degrees, is graduated with the ampères necessary to produce the various deflections, and thus the instrument is *direct reading*. When the iron of the tube has once become "saturated," the increase in the deflection is directly proportional to the increase in the current, a property which has various advantages in practice. The ends of the solenoid wire are attached to the two external binding-screws seen in the figure.

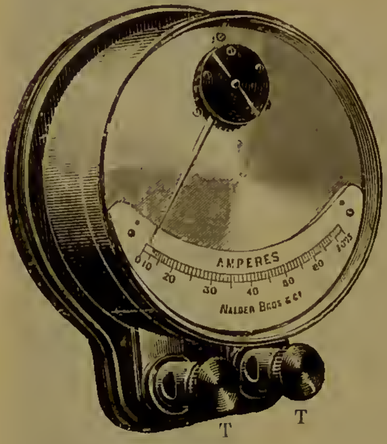

Fig. 194.—Nalder's Gravity Ammeter.

Finally, we shall describe a type of instrument which has come largely into use during recent years, and in which the controlling force is due to gravity. The particular instrument illustrated is made by Messrs. Nalder Brothers and Co. Fig. 194 shows the appearance of the instrument, whilst Fig. 195 gives front and side views, with the essential internal details. From the external terminals, T T, which in Fig. 194 are in front but in Fig. 195 are behind, the current is lead to a coil which is wound on the bobbin, *b b*, which has a large central hole, *c c*. In this hole is placed the soft iron needle, *n*, consisting of a bundle of fine wires attached by a lever arm to the axle, *a*, which is placed eccentrically in the hole—that is, the axle is a little below and to the left of the centre line of the coil. The pointer, *p*, is attached to the same axle, which works in jewelled pivots, and the whole pivoted system is then so balanced that when the instrument is placed in the vertical position, *p* points to the zero mark on the scale *s s*. The action of the instrument can now be easily understood. When the current flows through the coil, *b b*, a magnetic field is set up in the central hole, *c c*. This field is much weaker at the centre of the hole than near the boundaries. The soft iron needle, *n*, magnetised by this field, though not at the centre, is also not, when the pointer is at zero, in the strongest part of the field. It is so mounted that it is free to move further out from the centre, and actually does so, for, as we have already explained, a piece of soft iron placed in a non-uniform magnetic field always *tends* to move to the strongest part of the field. But as soon as it so moves, the force of gravity is called into play and *tends* to bring back the pivoted system to the zero position. As the drag of the magnetic field on the needle increases with the current, the pointer under the opposing forces takes up different positions for different currents. These positions are ascertained by actual experiment, and the corresponding currents marked on the scale, *s s*.

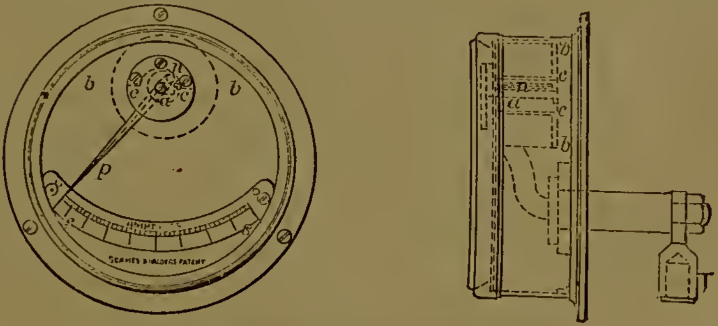

Fig. 195.—Details of Nalder's Gravity Ammeter.

Standard Galvanometers.

The Galvanometers we have now described measure the electric current, as we have pointed out on page 336, by measuring in various ways the strength of the magnetic field in its neighbourhood. Knowing the connection between the magnitude of the current and the strength of the magnetic field which it sets up under given circumstances, we ought to be able to calculate from the effect produced the magnitude of the current producing it. Unfortunately, in most instruments this is only theoretically possible, for the practical details of the calculation defy the powers of the most advanced modern mathematical analysis. The exact position of each bit of wire carrying the current would have to be known with greater accuracy than is possible in any form of sensitive galvanometer, and even if this initial difficulty were overcome, the calculation would still be too complicated for successful attack.

But by simplifying the instruments, enlarging the dimensions of the coils so as to make accurate measurement easier, and attending to the precautions indicated by theory, galvanometers can be constructed such that the current required to produce a certain deflection can be calculated beforehand. These instruments are called *Standard Galvanometers*, for by comparison with them the other and more sensitive instruments can be calibrated.

But first, what is the connection between the magnitude of the current and its magnetic field? This question is not easy to answer, as all the circumstances must be taken into account, but one of the simplest ways of stating it is the following, which may be taken as the **electro-magnetic definition** of the ampère :—*The current which, flowing in a conductor ten centimetres long bent into a circular arc of one centimetre radius, acts* **across air** *with a force of one dyne on a unit magnetic pole*[1] *placed at the centre, is called a current of one* **ampère**. This definition is illustrated in Fig. 196, which is drawn to scale. The current is to enter at *a*, and is to pass about $1\frac{7}{12}$ times round the spiral, which is of one centimetre radius, to *b*; if, then, the magnetic force, set up along the axis of the spiral at *f* in the direction of the arrow, is such as to act upon a unit magnetic pole placed there with a mechanical force of one dyne, the current is a current of one ampère. The reader should notice how very carefully all lengths and distances have to be specified in this definition, and how the necessity for this specification complicates it, as compared with the electrolytic definition given on page 305. The only awkward number in the latter is the quantity of silver deposited by one coulomb of electricity. Had the electrolytic definition preceded the electro-magnetic, a simpler number would probably have been chosen; but the magnitude of the ampère was originally fixed by the electro-magnetic definition, and the electrolytic number given by experiment as corresponding to that definition had to be adopted, or we should have had two conflicting units of current.

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[1] See p. 105 for the exact meaning of this term.

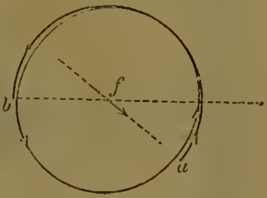

Fig. 196.—Magnetic Effect of One Ampère.

Now, it is practically impossible to make the current suddenly start into existence at *a* (Fig. 196) and disappear at *b*, because, as we know, all currents must flow in closed circuits. But we also know that the magnetic effect at *f* is proportional to the length of conductor carrying the current, provided *all parts* of that conductor are *equidistant* from *f*. Thus we are enabled to close up our circles and then dispose of the wires leading to the battery in such a way as to produce no magnetic effect at *f*. Also, since the force at *f* is inversely as the radius of the circle, we can use larger circles than those of one centimetre radius mentioned in the definition.

On these principles the *Tangent Galvanometer* is constructed. One pattern is shown in Fig. 197. The conductor consists of a nearly closed ring, *r r*, of copper strip; the lower ends of the strip, instead of meeting to complete the circle, are brought close together, turned sharply at right angles, and led to the two binding-screws, B, from which connections can be made with the rest of the circuit. The strip is kept in its circular form by being firmly clamped to a concentric and more massive ring, R R, which is grooved and carries a coil of many turns, whose ends are connected to the binding-screws, *a*, and which is used for measuring small currents. These coils are mounted so as to turn freely round the vertical pillar at the bottom, and this pillar is carried by the massive circular base, which is provided with levelling screws, so that the plane of the coils can be adjusted until it is truly vertical. At the common centre of the circles there is rigidly supported the box, M, containing the suspended mirror, with the little magnets at its back, as in the ordinary reflecting galvanometers. The mirror and magnets are suspended by a long fibre, which hangs down from the screw, *s*, at the top of the tube. The movements of the mirror and its magnets are observed in

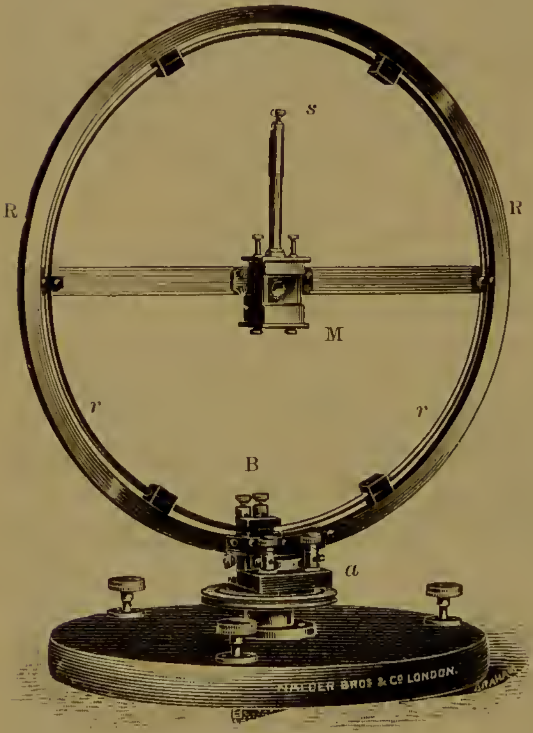

Fig. 197.—Standard Tangent Galvanometer.

the usual way, with either telescope or lamp and scale. The controlling field usually employed is that of the earth and the strength of this field has to be determined carefully by independent experiments.

In using the instrument it must first be set so that the plane of the ring, $r\,r$, lies in the magnetic meridian. It should then be carefully levelled until the little magnet and mirror lie at the centre of the large circle. If these adjustments are carefully made, we know that the lines of force at the needle, due to a current in the coil, will be *at right angles* to the lines of force of the earth's field. When this is the case, the conditions for the *tangent law* referred to below, and from which the instrument takes its name, are fulfilled.

When the instrument is properly constructed and adjusted the calculation of the current that will produce a particular deflection is very simple. Thus, if C be the current in the ring, in ampères, and r the radius of the ring, measured in centimetres, we know that the length of the ring is $2\,\pi\,r$ (where $\pi = 3{\cdot}142$), and that the strength of the magnetic field at the centre is

$$= \frac{2\pi r C}{10 r^2} = \frac{\pi C}{5 r}\,.$$

If now H be the ascertained strength of the earth's controlling field, the needle will take up such a position that the *tangent of the angle* of deflection (A) is equal to the ratio of the strengths of these two fields. Thus we have

$$\frac{\frac{\pi C}{5 r}}{\mathrm{H}} = \tan \mathrm{A},$$

whence

$$\mathrm{C} = \frac{5\,\mathrm{H} r}{\pi} \tan \mathrm{A}.$$

For a given angular deflection, A, all the quantities on the right-hand side of this last equation are known, and, therefore, the current, C, that will produce that deflection can be calculated. Thus, if *r r* be 50 centimetres (about 20 inches) in diameter, the current required to produce a deflection of 45° in London will be very nearly equal to 7·16 ampères. A slight correction must be introduced, because of the small gap in the circle at the lowest part.

The sensitiveness of the tangent galvanometer may be increased by replacing the single conducting ring of metal by several turns of wire wound in a groove, and diminishing the diameter of the coil.

For a first approximation, the formula already given for the current, C, that will produce a deflection A in this galvanometer may be used; but *r* must be the mean or average radius of all the turns, and the right-hand side must be divided by *n*, the total number of turns in the coil. For exact standard work, corrections must be made for the displacement of some of the turns from the plane containing the centre of the magnet; but into the details of these we need not enter. The point to notice is, that though we gain sensitiveness, we also complicate the calculations required for exact work.

All these galvanometers, as their name implies, follow a *tangent law*—that is, the currents are not proportional to the *angular* deflections they produce, but to the *tangents of the angles.* If, therefore, the scales are graduated in ordinary degrees, a table of tangents must be used to obtain the relative values of the various deflections. It is thus more convenient to at once mark the scale with numbers proportional to the tangents of the various angles, instead of marking the angles themselves; this scale will then at once give the relative values of the currents which produce the different deflections. Such a scale is represented in the lower half of Fig. 198, which is a copy of the scales often supplied with tangent galvanometers. The numbers on this lower half are directly proportional to the currents which will produce the various deflections. The upper semicircle is graduated in ordinary degrees, so that the observer may use either the complicated or simple method of observation.

The galvanometers just described are *standard* instruments in the strictest sense of the word, in that the current producing a given deflection can be calculated when the details of construction are known. The term, however, is sometimes applied to instruments in which the current cannot be so calculated beforehand, but *whose calibration is not liable to change:* that is, instruments in which the same current may reasonably be expected *always* to produce the same effect. On these instruments the *controlling force* is usually *non-magnetic*. The Siemens' Electro-dynamometer, already described (page 365), is of this type, since, with moderate care, the controlling force of the cylindric

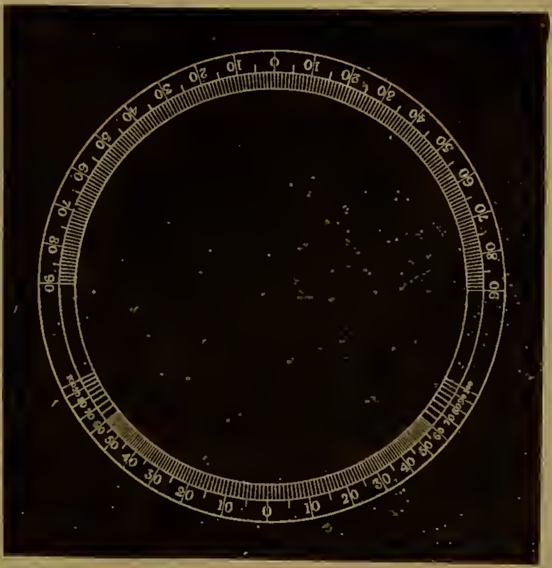

Fig. 198.—Scale for Tangent Galvanometer.

spiral spring should remain unchanged for many years, and the interacting coils always have the same relative position.

To another type belong the so-called *current weighers*, in which the attractions of co-axial coils are balanced against a gravitation force. These instruments have recently been brought to great perfection by Lord Kelvin, who has successfully overcome numerous practical difficulties in their construction. The method was also employed by Lord Rayleigh in 1884, in his classical research on "The Electro-Chemical Equivalent of Silver."[1] The principle is illustrated diagrammatically in Fig. 199. A coil of wire, *a* (shown in section), is suspended from the beam of a balance so that the planes of the windings are horizontal. Another coil, A, is placed below it on a horizontal table, and

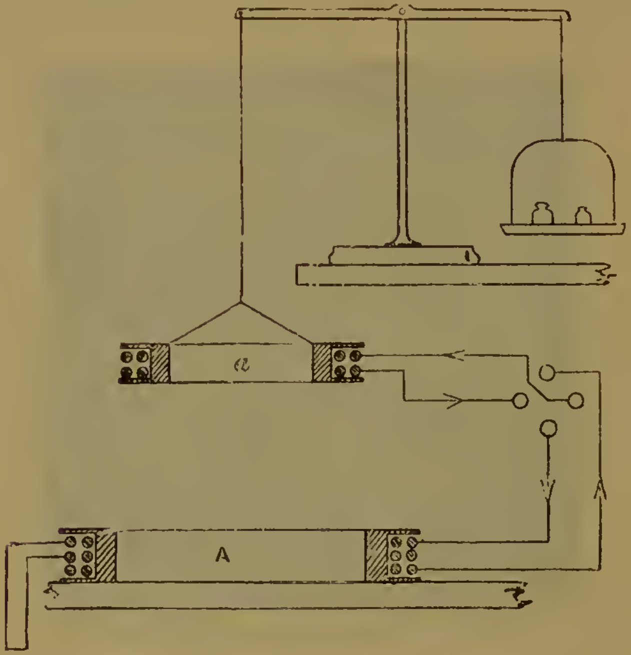

Fig. 199.—Principle of the Current-Weigher.

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[1] See *Philosophical Transactions*, 1884, Part II.

so that the axes of the two coils coincide. Connections are arranged by which the current to be measured, or *weighed*, can be passed through the two coils placed in series, and the figure also shows a commutator, by which the current can be reversed in *a* without its direction being altered in A. The wires by which the current is led to and from *a* are placed so as to disturb the action of the balance as little as possible; the coil, *a*, is counterbalanced by weights in the opposite scale-pan, and its position is accurately noted before any currents are passed through. On passing the current, the coils either mutually attract or mutually repel one another; if the currents in the two coils are both in the same direction—*e.g.*, both clockwise, as seen from above—there is attraction; whereas if they are in opposite directions there is repulsion. The forces thus brought into play are counterbalanced by altering the weights in the scale-pan until the suspended coil returns to its original position; or, better still, balance is first obtained when the currents are repelling, and then by means of the commutator the current in *a* is altered, so that the repulsion becomes an attraction, and the additional weights necessary to restore equilibrium and bring *a* back to its zero position are added. These weights measure the forces acting between the two coils which, in their turn, are simply proportional to the currents in each, and thus these currents are, as it were, *weighed;* hence the name given to the instrument. In actual use, another coil, similar to A, is placed above *a* in a symmetrical position, and the current is also sent through it in such a direction that it tends to re-enforce the action of A, and thus the effect, being increased, can be more accurately measured. This coil has been omitted in the figure for the sake of clearness.

When the coils are not too small or too close together, the current that sets up the measured force between the coils can be calculated from the details of construction and the relative position. It was in this way that Lord Rayleigh used the instrument as a standard for the absolute measurement of currents.

In Lord Kelvin's modification the coils are brought very much closer together, in order to increase the sensitiveness; the currents can then be no longer calculated from the observations, but the instrument belongs to the *second* class of standard instruments referred to above. It is made in several ways, to suit different ranges of current. The particular one shown in Fig. 200 is known as the centi-ampère balance, and measures currents ranging from $\frac{1}{100}$ to $\frac{1}{2}$ of an ampère. There is a coil attached to each end of the balance arm, which is, of course, movable, and each of these coils is placed midway between and co-axial with two fixed coils, so that there are six coils in all placed electrically in series with one another. The electrical connections are such that when the currents in the fixed coils on the left cause the coil between them to tend to move upwards, the currents in the right-hand coils tend to move the coil between them downwards, so that both effects tend to rotate the arm of the balance in the same direction. The axle of the balance can be seen in the centre of the figure, and also the numerous fine wires by which the current is conveyed between the fixed and movable parts.

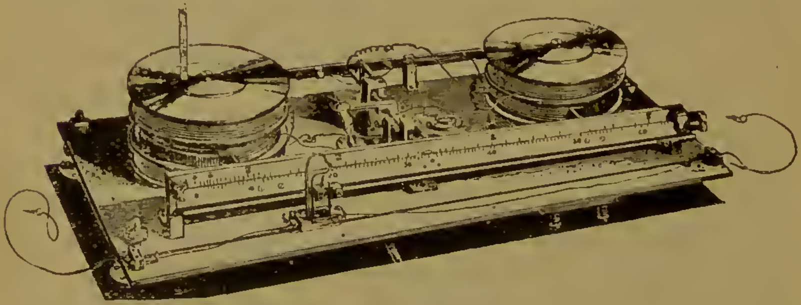

Fig. 200.—Lord Kelvin's Centi-Ampère Balance.

At the front the coils and axle are attached to the bar on which the lower of the two scales is engraved, and at the right-hand end this bar carries a pointer which moves over a short vertical scale, and indicates when the balance is in equilibrium. When currents are flowing through, the beam is brought to the zero position by moving along it the little travelling carriage, until its weight and leverage counterbalance the electro-magnetic forces. When in use, the balance is covered with a square glass case, and the little carriage is moved backwards and forwards by means of a self-releasing pendant hanging from a hook, carried by the sliding platform, which is worked by the silk cords from the outside. The position of the carriage is indicated on the beam by a pointer attached to it, and from this position, when equilibrium is attained, the current is known. By putting different known weights on the movable carriage, the range of the instrument can be varied.

Use of Galvanometers.

Before we leave this part of the subject, we may devote a line or two to a point which is often extremely puzzling to amateurs when they first begin to measure currents with galvanometers. In speaking of the sensitiveness of a galvanometer, that instrument is, of course, considered the most sensitive that gives the greatest indication with the smallest current. But when one has to use a galvanometer under given circumstances, one must remember that the introduction of a galvanometer into a circuit increases the resistance of the circuit, and, therefore, by Ohm's Law, diminishes the current. The most sensitive galvanometers that we have described have very high resistances, amounting to tens, and sometimes to hundreds, of thousands of ohms. Suppose now we have a circuit of a few ohms resistance, and we wish to measure the current in it by means of a galvanometer: if we were to introduce into the circuit a galvanometer of 10,000 ohms resistance, we would cut down the current to about one ten-thousandth of its former value, and would not be measuring this former value at all. But if our galvanometer has a resistance of only a fraction of an ohm, the effect on the current when it is introduced into the circuit may be quite negligible, and we shall be able to measure very approximately the original current.

A similar case occurs in the use of thermometers. Any cold thermometer introduced into a hot liquid to measure its temperature must, of course, cool the liquid. If the mass of the thermometer be small compared with the mass of the liquid, the cooling is inappreciable, and we obtain very approximately the temperature of the liquid before the thermometer was introduced. But if the mass of the thermometer bulb be much greater than the mass of the hot liquid, such as would be the case if a cold bulb two inches in diameter were introduced into some hot liquid in a teacup, the introduction of the thermometer so lowers the temperature of the liquid that the final temperature given by the instrument only enables us to guess very vaguely, and by calculation, at the value of the original temperature.

We may even go a step further, and enunciate the apparent paradox that for some kinds of work a galvanometer wound with a few turns of thick wire is more sensitive than one wound with many turns of fine wire, though the former cannot detect so small a current as the latter. The paradox is explained by carefully considering the application of Ohm's Law to the two cases. A little thought will show that, other things being equal, a low resistance galvanometer will be most sensitive for circuits of low resistance, and a high resistance galvanometer for those of high resistance. In the former, the current would be enormously reduced by introducing the high resistance galvanometer, so that what would be gained in sensitiveness would be lost in current. But in high resistance circuits the current is already small, by reason of the high resistance, and therefore a galvanometer of many turns of wire, and on that account of high resistance, is required to detect its presence. By the proviso, "other things being equal," we mean that the two galvanometers compared are of the same pattern and size, and with the same structural details, and that the only difference between them is in the length and thickness of wire wound on their coils.

THERMAL METHODS.

The exact measurements of electric currents by means of their thermal effects involves a thorough knowledge of, and practical acquaintance with, the laws of heat to a greater extent than a knowledge of the laws of the current. It would, therefore, lead us too far away from our immediate subject if we were to describe in detail all the precautions and devices that must be used to obtain an accurate measurement of the value of a current by these means. There are, however, instruments which use for purposes of measurement some secondary heat effect, although they do not measure currents by the actual quantity of heat generated in a known resistance in a given time. The particular effect made use of is usually the expansion of a flexible wire, caused by the heat generated in it by the electric current. As the wire has to be flexible, it is necessarily a fine wire, and hence the currents used are much smaller than those employed in heavy electrical engineering. The instruments are, therefore, usually employed not to measure the current passing through, but the pressure at the terminals, by a method to be described presently. These instruments will, therefore, be more appropriately described in the next section.

(*c*).—Electro-motive Force.

We pass on now to consider very briefly how the electro-motive force (E.M.F.), or total electric pressure in a circuit, may be numerically expressed and measured. In doing this, we shall describe incidentally, if not chiefly, the methods by which the electric potential difference (P.D.), or electric pressure between any two parts of a current-carrying conductor, is tested. It is this latter P.D. which is of the greatest importance to the user of the current. The full E.M.F. can be estimated from it when all the data concerning the various circuits are known, but this E.M.F. is not always in itself capable of direct measurement, because in many cases, notably with dynamo machines, the stoppage of the current in order to allow the full pressure to become manifest so completely alters the conditions of production as to make the measurement of no value. Even with batteries, as we have seen (page 44), the available working E.M.F. is, on account of polarisation, not as great as the pressure between the terminals on open circuit when the battery has been lying idle for some time.

One of the most usual ways of measuring the P.D. between two points in a circuit in which a current is flowing is to make use of the fact that, according to Ohm's Law, the P.D. will send a certain current through a fixed resistance. If, then, this fixed resistance includes a galvanometer which is capable of measuring the current passing through it, the product of this current (**C**) by the fixed resistance (**R**) will give us the P.D. ($\mathbf{V}=\mathbf{C}\ \mathbf{R}$), which causes the current. Now, as this measurement must be made without stopping the flow of the current in the original circuit (for the stoppage might, and usually would, alter all the conditions), it is evident that the galvanometer, with its fixed resistance, must be in a shunt[1] or parallel circuit between the points under consideration.

The principle of the method will be better understood by reference to Fig. 201. The upper part of the figure represents the general case; a current maintained by some electric generator, not shown in the figure, is flowing from *x* to *y*, and it is required to measure the potential difference between two points, A and B, on the conductors. To do this, a branch circuit, A V G B, is arranged, consisting of a galvanometer, V G, of known resistance, and if necessary, an additional known resistance, *r*. If the galvanometer is a *direct-reading* instrument, showing at once the number of

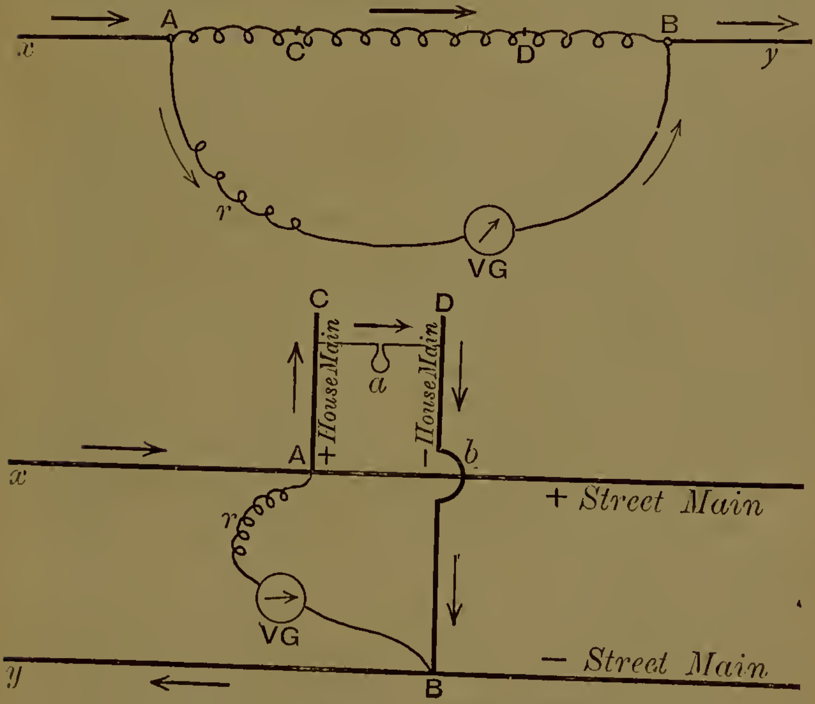

Fig. 201.—Measurement of Potential Difference.

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[1] This phrase is fully explained at page 288, as well as in what follows.

ampères or the fraction of an ampère that is passing through it, then the product of this current by the total resistance of the branch A V G B will give the P.D. between A and B *at the moment the measurement is made.*

The lower part of the figure is intended to represent diagrammatically the measurement of the P.D., at which current is supplied to a house from public supply mains in the street. x A and y B are respectively the positive (+) and negative (−) mains of the supply company. At A and B, the + and − house mains A C and B D are attached. The current enters the house at A and leaves at B, and finds its way from A C to B D through the lamps, motors, and various appliances in the house; one of these is shown at *a*, and we are not now concerned with their number or purposes.[1] The question is to measure the P.D. between A and B, as this is one of the factors of the electric energy delivered to the house. We proceed in exactly the same way as in the general case. A galvanometer, V G, with an additional resistance, *r*, if necessary, is joined up to A and B, and the current passing through this branch circuit measured. The product of this current by the known resistance of the branch A V G B, will be the P.D. between A and B.

A simplification of the process at once suggests itself. If the same additional known resistance, *r*, be always used with the same galvanometer, V G, or, better still, if the resistance of the galvanometer itself be sufficiently great to render this additional resistance unnecessary, the *same P.D.* will always produce the *same deflection* of the galvanometer. Therefore, instead of marking the scale of the galvanometer in ampères, it may be at once marked in *volts*, and the instrument may then be called a *Voltmeter Galvanometer*, or, more briefly, a **Voltmeter.** Such instruments are now manufactured in large numbers.

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[1] The loop at *b* is one of the conventional ways of indicating that the conductor B D crosses the conductor x A without making electrical contact with it.

Before proceeding further, we may as well give here a formal definition of the volt. *The* **Volt** *is the Potential Difference that must be steadily maintained between the ends of a metallic conductor of* **one ohm** *resistance in order that the steady current flowing through it may be* **one ampère.**[1]

We have now to explain why it is necessary, in measureing the P.D. between A and B (Fig. 201), to use a high resistance in the branch circuit A V G B. One of the first conditions of the scientific and accurate measurement of any physical quantity is that the method employed shall not alter the magnitude of the quantity to be measured. We have already dwelt upon this condition, and illustrated it when speaking (page 381) of the "Use of Galvanometers." But in measuring potential differences indirectly by voltmeters, the necessity of bearing this limitation in mind is of even greater importance than in using galvanometers to measure currents directly. Returning to Fig. 201, what is the effect of putting on the branch circuit A V G B? This in great measure depends on the conditions of supply.

Take first the simple case of a battery of constant E.M.F. being used as an electric generator. The resistance between A and B is then only a part of the resistance of the circuit; but the addition of the branch A V G B reduces (*vide* page 288) the resistance between A and B, and therefore increases the total current drawn from the battery. Of this increased current, however, part only goes along the main branch, A C B, and the remainder along A V G B, and it is easy to show that as long as A C B is not the only resistance in circuit, the current now going along A C B is *less than it was before the branch-circuit was added.* Therefore the P.D. used to maintain this current in A C B is less, and the method of measurement has altered the thing to be measured. But a little reflection will show that the *greater the resistance* of the branch-circuit the *less is the disturbance.* Thus if the resistance of A V G B be a hundred times the resistance of A C B, the putting on of this branch will diminish the resistance between A and B about one per cent.; the total current will therefore be increased less than one per cent., and as ninety-nine per cent. of this current goes through A C B, the current therein and the P.D. of A and B will be diminished less than one per cent. This may be accurate enough for most purposes, but if greater accuracy be required, the resistance of the branch A V G B must be made 1,000 or 10,000 times that of the main A C B, and a more sensitive galvanometer used; the error will then be reduced to one-tenth or one-hundredth of one per cent. As sensitive galvanometers are, *cæteris paribus*, of high resistance, they easily fulfil the condition.

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[1] It is assumed that there is no source of E.M.F. in the conductor.

Suppose next that the conditions of supply are such that by proper regulating devices the total current supplied is always the same. When this current reaches A it must divide between the branches A C B and A V G B, and therefore the current passing along A C B will be less than if the branch A V G B were not joined on. But by Ohm's law the two parts of the current are in the *inverse* ratio of the two resistances, and therefore by *increasing the resistance of the branch* A V G B, the amount of the current drawn off along it may be so small as to leave the current in A C B *practically* unchanged, and yet this small current may be quite large enough to be measured on a sensitive galvanometer. For instance, it may be only the one-millionth part of the current in A C B, but for this to be the case the resistance of the branch A V G B must be one million times that of the main A C B.

Lastly, suppose the conditions of supply are such that the P.D. of A and B is maintained constant, no matter what the resistance may be between A and B. This would be the case in the public supply system represented in the lower figure. The mere addition of branch circuit A V G B between A and B will not now affect the P.D. to be measured, but another consideration still causes us to put as high a resistance as possible in this branch circuit. For a galvanometer whilst a current is passing through it uses up energy by converting it into unavailable heat; also *when the P.D. is constant the heat energy* produced by a current *varies inversely as the resistance.* Now, wasted energy has always to be paid for in some way, therefore in making electrical measurements we endeavour to use up as little energy as possible. In this case that is accomplished by using the greatest possible resistance, and therefore a sensitive galvanometer in the voltmeter branch.

Thus in all cases that arise in practice, the voltmeter should be a galvanometer of high resistance, having a range adapted to the particular voltages to be measured.

Magnetic Voltmeters.—From what we have just said it will be apparent that any galvanometer that is sufficiently sensitive may be used as a voltmeter, and therefore the various instruments described in the last section are available.

In particular, for commercial purposes, all the "Galvanometers for Measuring Large Currents" can, by a very simple change, be converted into direct-reading voltmeters. We have pointed out that as ampèremeters their resistance must necessarily be very low, and therefore their conducting coils consist of a few turns of stout or thick wire. If, now, keeping all the magnetic and mechanical details unaltered, we wind the conducting coil with many turns of fine wire, we shall have a high-resistance voltmeter instead of a low-resistance ampèremeter. Then, instead of graduating the scale with the ampères flowing through, we graduate it with the volts of potential-difference, which on being applied to its terminals can maintain the currents that produce the various deflections. We thus have a *direct-reading voltmeter*.

In Fig. 202 we give an outside view, showing the scale of such an instrument. This particular voltmeter is in every respect similar to the ammeter described on page 370, except that it is wound with many turns of fine wire instead of a few turns of thick wire, and also it has its scale graduated in volts of potential-difference at its terminals instead of in ampères of current passing through it. Thus when the indicator points to 70, we infer that the P. D. between the binding screws of the instrument is 70 volts.

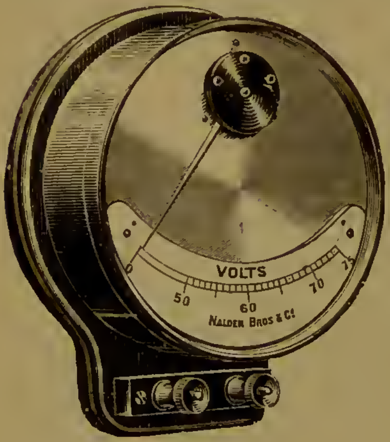

Fig. 202.—Direct-Reading Voltmeter.

Thermal Voltmeters.—Although the thermal effect of the current does not lend itself very readily to the accurate measurement of the currents used for electric lighting and other public purposes, a subsidiary effect of the heat generated has been employed by Major Cardew to measure the currents used in voltmeters. The various difficulties in the way of the production of an accurate and reliable instrument have been very ingeniously overcome, and the result is the widely-used and well-known Cardew Voltmeter.

The principle of the instrument will, perhaps, be best understood by reference to the diagram in Fig. 203. Suppose L to be a movable pulley, and A C D B to be a long iron wire, with both ends, A and B, fastened to the ceiling, and passing round and supporting the pulley, L. The pulley, L, by means of the hook, K, supports a weight, W, which is just heavy enough to keep the wire stretched without overstraining it. Flexible wires, P and N, soldered to A and B, can be used to supply current. If now a current be passed from P to N, through the wire in the direction of the arrows, heat will be generated in the wire, and it will get hot. But iron and all metals expand on being heated, and, therefore, the wire will become longer, and the ends being fixed, the weight, W, will drag down the pulley, L. Thus, as the wire gets hotter and hotter, the weight, W, will sink lower and lower, until such time as the radiation from the wire is equal to the rate at which heat is generated in it by the current. The weight, W, will then remain stationary as long as the current is maintained steadily. If the current diminishes, the rate of production of heat falls, the wire cools to some lower temperature, corresponding to the new rate of production and radiation of heat, and the weight, W, rises, by the shortening of the wire, to some other fixed position. If, on the other hand, the current increases, the temperature and length of the wire will increase, and the weight will fall to some other position. Therefore, if the wire were carefully protected from outside thermal influences, accurate observations of the position of the weight would

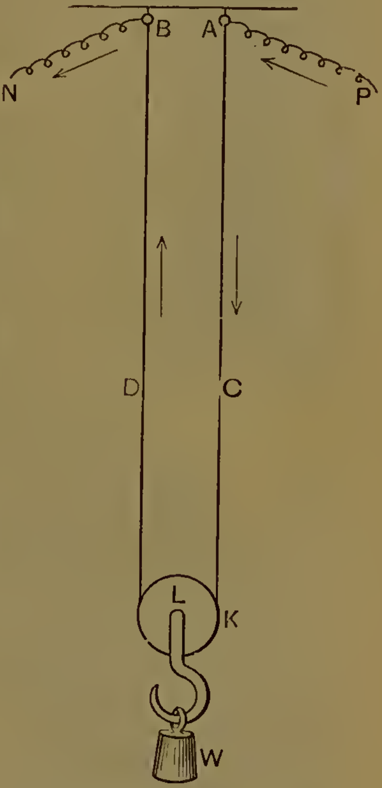

Fig 233.—Principle of Cardew's Voltmeter.

enable us to estimate from previous calibrations the magnitude of the current flowing in the wire, or the magnitude of the P.D. between its ends A and B. In the actual instrument the weight, W, is replaced by a stretched spring, and the motion of the pulley is mechanically magnified; also other refinements are introduced, which will be best understood from a brief description.

The back of a recent form of Cardew's Voltmeter, with the cover partly removed to exhibit the working parts, is shown in Fig. 204. The stretched wire, through which the current passes, is made of platinum silver, and is 0·0025 inch in diameter, and about 13 feet long. One end being fixed to the screw, A, the wire passes up a tube (removed to show the wire) about 3 feet long, over the fixed bone pulley, P_1, then down the tube and under the little *movable* pulley, p_1, up the tube again, and over the fixed pulley, P_2, and finally down the tube to the screw, B. The block of the movable pulley, p_1, is attached by a fine and flexible thread to the coiled and stretched spring, S_1, and this thread passes once round the fixed pulley, W. Thus, the platinum-silver wire is kept stretched by the pull of the spring, S_1, and whenever the length of the wire alters, the wheel, W, is partly turned. The axle of the wheel, W, carries the toothed wheel, L, which works in the pinion, M, on the axle of which the pointer is carried, which moves over the face of the dial, of which the figure only shows the back. The screws, A and B, are metallically connected to the external binding screws, T_1 and T_2. If now the P.D. to be measured be applied to T_1 and T_2, the platinum silver wire will become heated, and lengthen, as already explained; the pulley, p_1, will be pulled down; the wheel, W, slightly turned; and the index moved round the dial. The potential-differences corresponding to the various deflections are determined by previous experiment, and marked on this dial.

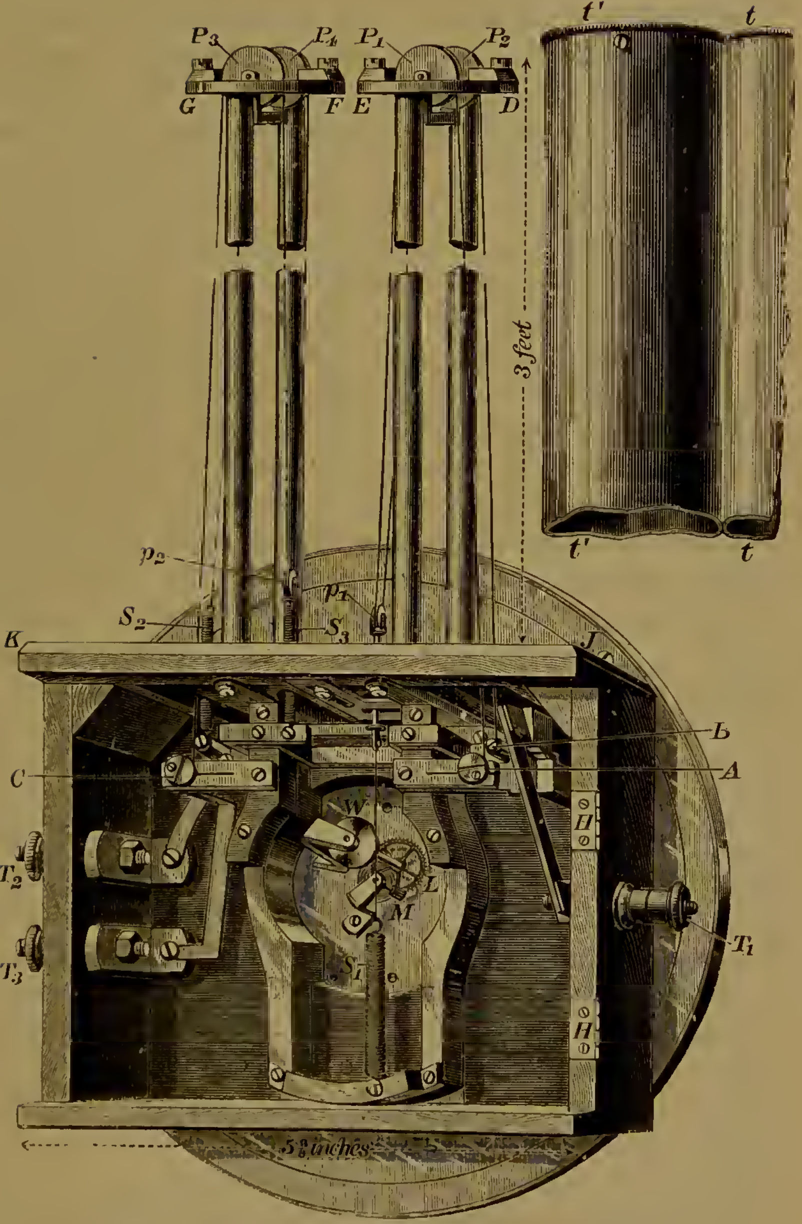

FIG. 204.—THE CARDEW VOLTMETER.

In order that the range of the instrument may be doubled, an extra wire of the same length and resistance is added in the tube to the left of that containing the working wire. This wire is kept taut by the springs, S_2 and S_3, and its disposition in its tube is precisely similar to that of the working wire. One end of it is fastened to the screw, C, which is connected to the binding screw, T_3. When the binding screws, T_1 and T_3, are used instead of T_1 and T_2, the two wires are in series, and the same current passes through each. They are, therefore, equally heated, and if their resistances are equal at the commencement, they remain equal for all currents. Thus, since the current has now to pass through double the resistance, it will require double the P.D. to produce the same movement of the pointer, as when the terminals, T_1 and T_2, were used; the range of the instrument is, therefore, doubled. On the face of the dial two sets of graduations are engraved, one of lower numbers, to be read when the terminals, T_1 and T_2, are used, and the other of higher numbers to be read when T_1 and T_3 are used.

The fine wires are protected by the metal tubes, *t t*, *t′ t′*, which slip over and support the discs, D E and F G, that carry the fixed pulleys. To correct for changes in the temperature of the room, the rods that carry the discs are made partly of iron and partly of brass, in such proportions that their mean coefficient of expansion is equal to that of the platinum-silver wire.

Electrostatic Instruments.—On theoretical grounds, by far the best instruments for measuring electric pressures, either electromotive forces or potential-differences, are those whose action depends, not upon the magnetic effect of a current of electricity, but upon the attractions and repulsions of statically-charged conductors.

We do not propose to describe and discuss here the whole range of phenomena usually included under the term

"Electrostatics," though these phenomena are extremely interesting and most suggestive as to the nature of the entity that we call "Electricity." It will be sufficient for our purpose if we briefly state some of the experimental facts upon which the working of the class of instruments we wish to describe is based.

In our historical introduction (pages 6 to 16) are briefly summarised the chief discoveries in electrostatics, and amongst other things, we have referred to the fact that similarly charged bodies repel one another, and dissimilarly charged bodies attract one another. If now we can construct an instrument partly of fixed and partly of movable conductors, in such a manner that the charges causing attraction or repulsion between the fixed and movable conductors are determined by the potentials whose difference we wish to measure, then by measuring the attraction or repulsion, we shall have indirectly a measure of the potential-difference. An electric pressure measurer working upon these principles is called an **Electrometer.**

The celebrated law of electric action, experimented upon by Coulomb and Cavendish, and developed mathematically by Laplace, Biot, Poisson, and others, states that, "*The attraction or repulsion between two quantities, q and q', of electricity supposed concentrated at two points at a distance d apart, is* $\frac{q\,q'}{d^2}$, *and is in the line joining the two points.*" This is exactly similar to the law of magnetic action enumerated on page 105, and is open to the objections which we have urged at page 107, against all "action-at-a-distance" theories. The above customary statement of the law makes no mention whatever of the influence of the medium between the two charges in modifying the action. As in magnetic, so in electrostatic phenomena, Faraday was the first to grasp the importance of taking the medium into account, and in one of his series of experiments he numerically estimated the differences in the actions of various media. He considered the action to be due to strains and stresses set up in the medium, and he graphically represented the kind of strain by means of lines of *electric force* exactly analogous to the lines of magnetic force upon which we have dwelt so fully. That these strains actually exist, and are not mere philosophical abstractions, is proved by the beautiful electro-optic experiments of Dr. Ker, of Glasgow, and of Professor Rücker in "Electrical Stress,"[1] experiments which we regret we have not space to describe in detail. Our present purpose is merely to explain the construction and action of electrometers.

Returning now to the conditions already enumerated, we notice that the potentials of the conductors of our instrument must determine the charges of electricity and the strains in the medium. Now, the potential required to impart a specified charge to a given conductor depends not only on the size and shape of the conductor, but also on the sizes, shapes, and positions of neighbouring conductors. But since the work done in charging a conductor depends both on the potential and on the charge, this is only another way of saying that the energy used in imparting the charge depends upon the nature, magnitude, and disposition of the medium in which strains are set up by the charge. If this medium be widely extended, the strains are feeble, and the energy required to produce them is small, but if the medium acted upon be a narrow gap between two conductors very close together, the strains may become very great, and the corresponding energy elastically stored in the medium, also great. One point, therefore, to be kept in view in designing an electrometer, is to confine the action as much as possible to a small portion of dielectric.[1] This is also the condition indicated by the old law, for the magnitude of the force being inversely as the square of the distance between the acting bodies, the shorter the distance the greater will be the force.

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[1] The reader who wishes to pursue the subject will find these experiments described in the *Journal of the Society of Telegraph Engineers*, vol. xvii. (1888), p. 310.

For instance, suppose A and B (Fig. 205) to be two metallic plates, of which one, B, rests on the table, and is, therefore, in connection with, and at the zero potential of the earth; the other, A, is supported above and parallel, but very close, to B by some insulating support. If now A be given a charge of positive electricity, and thus be raised to a higher potential than the earth, by far the greatest part of the electric action in the space surrounding A will be confined to the narrow gap between A and B. The result will be an attraction between A and B depending upon the size of the plates and their distance apart, and proportional to the *square of their potential-difference.* The attraction may be measured by balancing it against known forces; thus A may be suspended from the beam of a balance, and the attraction counterpoised by weights added to the scale-pan at the other end of the beam. From the known value of the weights, and the known dimensions of A and B, the value of the potential-difference can be calculated in volts.

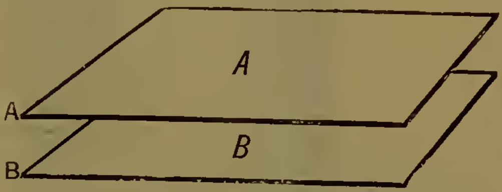

Fig. 205.—Attraction of Charged Parallel Plates.

Unfortunately, the attraction between two plates of manageable size is extremely small, except when the difference of potentials is a large number of volts. For instance, if the plates be 10 inches square and only a quarter of an inch apart, a potential-difference of about 300 volts is required to give an attraction equal to the weight of a grain.

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[1] The "*dielectric*" is the term used by Faraday to denote the medium across or *through* which the electric actions take place.

When it is remembered that the force is proportional to the *square* of the potential-difference, it will be at once seen how the attraction produced by the electric pressure of a single voltaic cell must be almost inappreciable.

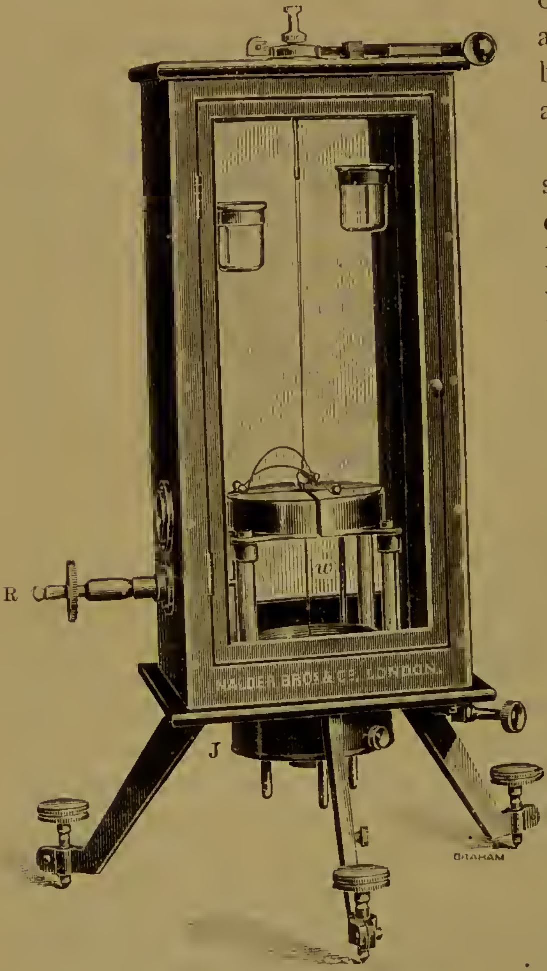

Fig. 206.—Kelvin's Quadrant Electrometer.

Notwithstanding this difficulty, Lord Kelvin has devised a series of beautiful instruments in which, by making use of an auxiliary electrification of one of the plates, to increase the attractive force, and by measuring the *difference* of the distances of the other plate necessary to produce a definite attraction when it is electrified first to one potential and then to the other, he has been able to measure directly potential-differences as small as one volt. The two instruments of the series capable of working with this degree of sensitiveness he calls the "Absolute Electrometer" and the

"Portable Electrometer." The force that balances the electric attraction is the torsion of a fine platinum wire; but the details of the instruments are somewhat complicated, and chiefly of technical interest. A much more widely known and a more sensitive instrument for measuring the *relative* values of two P.D.'s is Lord Kelvin's "Quadrant" electrometer, a simple modification of which we shall now describe. The instrument is shown in perspective in Fig. 206, and the chief parts, or "quadrants," upon which the electrical action depends and from which it takes its name, are shown separately and on an enlarged scale in Fig. 207. The quadrants A, B, C, D (Fig. 207) would, if joined together, form a shallow closed brass box with a central hole. They are, however, slightly separated from one another, and supported independently on insulating columns of glass, as shown in Fig. 206. Opposite pairs of quadrants are joined by conducting wires, so that A and C form, as it were, one insulated conductor, and B and D another insulated conductor. It is the potential-difference between these two conductors that is measured by the instrument; to connect them to outside conductors, two long brass rods pass from A and D down through the bottom of the case to two terminals on the far side, not shown in Fig. 206. A third insulated conductor, N, swings freely by an appropriate suspension within the hollow space enclosed by the quadrants.

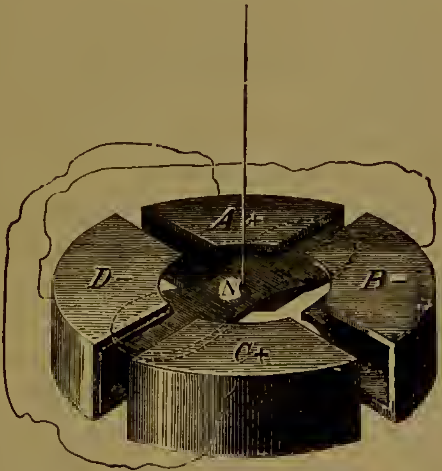

Fig. 207.—The Quadrants in Kelvin's Electrometer.

The conductor, N, is usually made of a thin corrugated strip of aluminium of the shape shown, and is electrically connected by the wire, *w*, with the inner coating of a Leyden jar, J, so supported that it can be readily withdrawn from the bottom of the case without disturbing the suspended needle. The inner coating of this Leyden jar, instead of being the usual tin-foil, is strong sulphuric acid, which serves the double purpose of acting as the coating and of keeping the interior of the case artificially dry.

The jar can be charged by the brass rod, R, which passes through an insulating ebonite collar, and has a piece of platinum wire hanging into the acid from its inner end. The wire, *w*, has also a little vane at its lower end, which, moving in the viscous acid, tends to steady the vibration of the needle. If now the inner coating of the Leyden jar be charged to a high potential, the needle takes the same potential, and carries a corresponding charge. It is so adjusted that when the quadrants are all at one potential, it lies centrally and in the middle of the box along one of the diametral slits. In this position, as long as there is no P.D. between the quadrants, there is no tendency for N to move, however highly it may be charged. But if one pair of quadrants, A C, be connected to the positive terminal of a galvanic cell, and the other, B D, to the negative terminal, A and C become positively charged and B and D negatively. If N, then, has a positive charge, it will be repelled by A and C and attracted by B and D, and will tend to rotate in a clockwise direction. This tendency is resisted by an appropriate controlling force, with the result that the angular motion of N is proportional to the potential-difference between A and D. This angular motion is read off in the usual way with a lamp and scale, and if the deflection corresponding to one volt has been ascertained, the deflection for any P.D. within the range of the instrument will give that P.D. in volts.

The controlling force used may be of various kinds. In Fig. 206 two silk threads hang down from the upper support at a little distance apart. When the needle, N, is in its zero position, these threads are parallel and vertical; but when N is rotated, they are no longer parallel and become slightly inclined to the vertical; N is therefore slightly lifted, and under the action of gravity tends to fall back to its zero position. This method of suspension, known as the *bifilar suspension*, can be adjusted so as to bring very small forces into play, and can therefore be made very sensitive. It is widely used for delicate work, because the controlling force is proportional to the deflection. Another method, shown in Fig. 207, is the *unifilar suspension.* In this case the suspension is a fine metallic wire attached to the top support, which must now be carefully insulated. When N deflects, the lower end of the wire is twisted, and the restoring force of torsion called into play is accurately proportional to the deflection. A third method sometimes used is the *magnetic control.* The needle is hung by a torsionless silk or quartz fibre, and little magnets are fixed on the back of the mirror seen in Fig. 206, just as in the reflecting galvanometers previously described. These magnets are not, however, affected by the electric charges, but, being placed in a magnetic field, always tend to turn the suspended system into one, the zero, position. When the system is deflected, the controlling force comes into play just as in the galvanometers, and subject to the laws already described in detail.

The quadrant electrometer has recently been still further modified by Professors Ayrton and Perry and Dr. Sumpner, with the object of making it still more reliable, especially for the measurement of alternating P.D.'s. Descriptions of these modifications will be found in the *Philosophical Transactions* for 1891.

STANDARDS OF ELECTROMOTIVE FORCE.

The practical definition of the volt on page 387, presupposes that the experimenter, who wishes to measure volts in accordance with the definition, is possessed of accurately calibrated ampèremeters to measure the current which is sent through accurate standards of resistance of known value.

Another definition of the volt is suggested by the remarks on page 397, according to which the volt might be defined as the potential-difference which would produce a certain mechanical force of attraction between two parallel plates of a certain size and certain distance apart, under carefully specified conditions.

The first of these definitions is by far the best, but is open to the objection that the means of producing the required current through the known resistance may not always be at hand. The second definition is, as we have seen, of little practical value, because the attractions in many commonly-occurring cases would be much too small.

An examination of the tables given in the discussion of the theory of the voltaic cell, and our remarks thereupon, will show that it ought to be possible to construct a cell of carefully-selected and pure chemical materials which should have a perfectly definite electromotive force. For if polarisation can be prevented, the E.M.F. depends only on the chemical constitution of the materials of which it is composed, and if these materials are sufficiently stable to remain unchanged during a considerable period of time, then, during that period, the E.M.F. of the cell will be absolutely constant. What this E.M.F. is can be ascertained experimentally by comparing it with a P.D. measured in accordance with the practical definition of the volt, and we shall then have an accurately-known electric pressure. By comparison with which, by well-known methods, the values of other pressures can be ascertained.

Cells constructed with the object of fulfilling these conditions are known as **Standard Cells**, and a vast amount of patient experiment and ingenuity has been devoted to the task of discovering the most suitable materials, and the best methods of so bringing them together as to preserve the E.M.F. of the cell unchanged for a long period of time. It will suffice to describe two of the forms which experience has shown to fulfil most nearly the conditions of the problem, though even these are not perfect, as we shall afterwards point out.

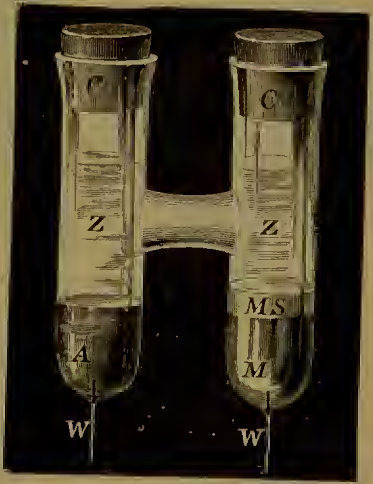

Fig. 208.—H form of Clark Standard Cell.

The cell which has recently been adopted by the Board of Trade as one which best fulfils all the conditions of a standard cell, has long been known to electricians, from the name of its inventor, as the Latimer Clark cell. Minute directions[1] for its construction have been published by the Board, guided by the skill and experience of an exceptionally powerful special committee appointed to advise the Board on the subject of electrical standards.

Without going so minutely into detail, we may say that the cell consists essentially of an amalgam, A (Fig. 208), of zinc and pure mercury, which forms the positive plate[2] of the cell, and a layer, M, of pure mercury forming the negative plate. These, in the pattern illustrated, are placed at the bottoms of two test tubes, ranged side by side with a connecting tube in the middle, forming a figure not unlike the letter **H**, from which the cell is sometimes known as the **H** pattern. Contact is made to the amalgam, A, and the mercury, M, by two platinum wires, W W, which are sealed through the glass of the tube. The mercury, M, is covered with a layer, M S, of pure mercurous sulphate, made into the form of a paste with distilled water, and the tubes are then filled with a saturated solution, Z, of pure zinc sulphate to a point above the level of the cross tube. To prevent evaporation, the tops of the tubes are either closed with corks, C C, made air-tight by marine glue, or are hermetically sealed.

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[1] *Vide The Electrician*, vol. xxvii. (1891), page 98.

[2] *See* page 42.

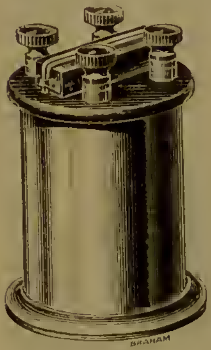

Fig. 209.—Clark Standard Cell.

When made up for use, the cells are enclosed in a brass case, as in Fig. 209, to protect them from injury. In the form shown in the figure, which is due to Dr. A. Muirhead, there are two cells, and therefore four terminals. As the E.M.F. of the cells depends upon their temperature, the bulb of a thermometer is placed inside the case and its stem is brought up and laid horizontally across the top, so that the temperature of the inside can be readily observed. One of the cells should be used for ordinary work, and compared from time to time with the other to ascertain if it is undergoing any change.

The E.M.F. of a Clark cell, carefully constructed with pure materials, has been shown by Lord Rayleigh to be very constant, provided the temperature be kept constant. Its value is **1·434 volts** at 15° C., but the variation with change of temperature is rather large, being nearly 1 unit in the last figure of the decimal for each centigrade degree difference of the temperature above or below 15° C.[1] The

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[1] The exact value at t° C. is

$$E = 1{\cdot}434 \left\{1 - 0{\cdot}00077\,(t - 15^\circ)\right\}.$$

E.M.F. diminishes as the cell gets warmer, and increases as it gets colder.

The constancy of the E.M.F. of the Daniell's cell, even when working under ordinary conditions, has led to many attempts to overcome the few outstanding difficulties, and numerous modifications have been proposed and used as standards of E.M.F. In all these the porous pot is dispensed with, as it introduces disturbances for which it is impossible to accurately allow. This introduces a fresh difficulty, as for standard purposes the two liquids of the cell must not be allowed to mix; or if they do, the mixed liquids must be removed before the cell is used. Several ways of meeting this difficulty have been proposed. The method described below was devised by Dr. Fleming, and this modification of the Daniell's cell is used as a standard of E.M.F. by the Edison and Swan United Electric Light Company, who were the manufacturers, for a long time, of all the high-resistance glow lamps used in this country.

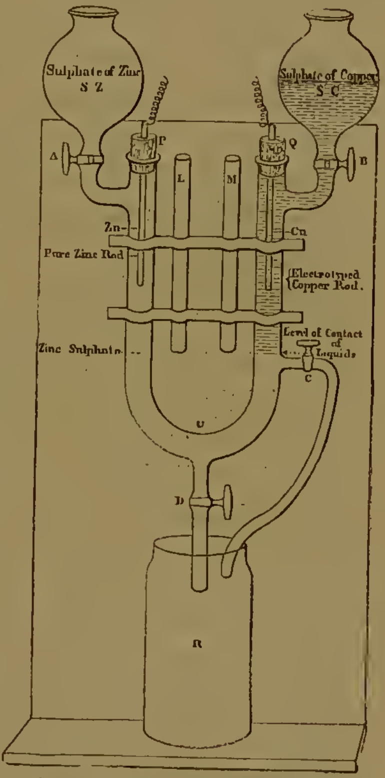

Fig. 210.—Standard Daniell's Cell.

The form of the cell, which is a little complicated, is shown in Fig. 210. It consists of a glass U tube, with an outlet at the bottom closed by a glass tap, D; there is also near the bottom of one of the limbs an opening, closed by a tap, C. Near the top of each limb are side tubes leading to the reservoirs, S Z and S C, communication with which can be opened or closed by means of the taps A and B. The positive and negative elements when not in use are kept in the tubes L and M. The former consists of a rod of *pure* zinc stuck through the rubber stopper, P, and the latter of a rod of *freshly electrotyped* copper stuck through the stopper, Q. The copper is electrotyped just before use by being placed in an electroplating bath (page 472) of copper sulphate, and having a thin layer of pure copper deposited on it. The reservoir, S Z, contains a solution of pure zinc sulphate, of a density of 1·400 at 15° C, and S C contains a solution of copper sulphate, of a density of 1·100 at the same temperature.

When the cell is to be used, the tap A is first opened and the U tube filled with zinc sulphate; the zinc rod is then put in its place, and the top of the left-hand tube closed tightly with the stopper, P. The tap, C, is then partly opened, and as the zinc sulphate flows slowly out of the right-hand limb, its place is taken by copper sulphate, which is allowed to flow slowly through the tap B. When this is carefully done, the line of demarcation between the white and blue solutions is perfectly sharp, and gradually sinks to the level of the tap C, and then both B and C are closed. The freshly electrotyped copper rod is now put into its place, and the cell is ready for use.

After standing some time the liquids diffuse into one another, and the surface of separation becomes blurred. When this happens the mixed liquid is to be drawn off from C, and fresh liquid supplied from the two reservoirs. The E.M.F., when the solutions are of the strength specified, is 1·072 volts at 15° C., and the change of E.M.F. for small variations of temperature is much smaller than it is in the Clark cell.

The great disadvantage of all voltaic cells as standards of electromotive force is the polarisation which takes place when they are allowed to send a current. Whenever possible, therefore, methods of testing should be used in which no current, or only a very small one, is required. In this respect the electrometer has a great advantage over the voltmeter, for it requires only a brief and inappreciable current to charge the quadrants. With regard to polarisation, the Daniell's cell is much better than the Clark, but it has the disadvantage of not being portable, for when once set up, any shaking of the cell mixes the liquids.

Power.

In the next electrical quantity, whose measurement we propose to describe briefly, the electrician enters upon a province which is of much interest to the ordinary engineer, and also to the general public. The custom of speaking of the power of large steam-engines, whether land or marine, as being so many thousands of horse-power, is one with which everyone who reads the daily papers must be familiar. Whether everyone has an exact notion of what is meant is another thing, and perhaps some of our readers may improve their ideas of the general principles involved by considering briefly the corresponding electrical problems. For in the modern industrial applications of electricity for electric lighting and for ordinary engineering purposes, one of the most important factors is the *power* of the electric current employed. Thus, to take one instance only, the question of utilising the energy of the Niagara Falls in distant cities, resolves itself into the consideration of how a large amount of power can be electrically transmitted with economy from the Falls to the cities.

What, then, is power—whether electrical or mechanical, or in any other form? It is simply the *rate of doing work*, or the *rate* at which energy is being transmuted from one form to another. If the *energy* is measured in *foot-lbs.*, that is, in terms of the amount of work required to raise a pound weight one foot high, then the proper unit in which to measure *power* is a *foot-lb. per minute* or *a foot-lb. per second.* Either of these units. however, is too small for the usual engineering work, and therefore James Watt introduced a larger unit which he called the *horse-power*, and which he defined thus:—

One horse-power = 33,000 foot-lbs. per minute.

Thus the horse that James Watt adopted as a standard—rather a good horse, by the way was able to work at a rate equivalent to the raising of a mass of 33,000 lbs. (about 15 tons) one foot high in a minute.

In electrical work the power is quite simply obtained, if we are able to measure the volts and the ampères; it is the product of the two, and the unit was formerly designated by the compound word *volt-ampère*, but is now known as the **Watt**, in honour of James Watt, who did so much to introduce exact ideas concerning power. Thus:—

One volt × one ampère = one Watt.

But if the Watt is a unit of power, it is only another way of measuring the rate of doing work, and must have a definite relation to the engineer's unit, the horse-power. Such is, indeed, the case, for it can be shown that

One horse-power = 746 Watts,

and therefore

One Watt = 44$\frac{1}{4}$ foot-lbs. per minute.

Thus 1,000 Watts (called **one kilowatt**) is, within a very small percentage, equal to 1$\frac{1}{3}$ horse-power. It is now quite customary to speak of the power of a dynamo machine as being so many kilowatts, and the reader will perceive how this corresponds to the engineers' method of speaking of the power of a steam-engine as so many horse-power. For smaller electrical work the Watt is a convenient unit; thus a nominal 2,000 candle-power arc lamp requires about 500

Watts, and a 16 candle-power glow lamp requires about 60 Watts when properly burning. For telegraphic signalling on an ordinary land line only, a fraction of a Watt is usually required, and except in large offices, primary batteries can conveniently supply the necessary power.

Now, in all the cases cited, and in others, the power supplied to any part of an electric circuit can be measured by measuring the current in *ampères* and the P.D. in *volts;* the product of the two will, *for steady*[1] *currents*, give the power in *Watts*. But measuring the power in this way we require two instruments, namely, a galvanometer (or ammeter) and a voltmeter. The various forms of these instruments have already been described. If, however, our only object is to measure electrical power, and we are, to some extent, indifferent to the current or the voltage, it will manifestly be advantageous to use an instrument which will at once *indicate the power*, and so save the trouble of double observations and subsequent calculation. Such instruments are called **Wattmeters**, and, though not yet very widely used, are interesting as a step in the direction of the next class of instruments, the energy measurers, which are of great public importance and interest.

Wattmeters.—If the conditions of supply are such that either the current or the pressure is kept constant and of a known value, then obviously a suitable voltmeter or ammeter can be graduated and used as a Wattmeter. For instance, if the current be always kept at 10 ampères, then the power supplied to any part of the circuit can be measured by placing a voltmeter across that part to measure the volts; the volts multiplied by 10 will give the power in Watts, and a scale of Watts might be marked on the instrument instead of volts.

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[1] The modification of this proviso, due to the imperfections of the instruments used, in the case of alternate and fluctuating currents, will be dealt with later (page 449).

On the other hand, if the pressure maintained between two points on the circuit be always 100 volts, an ammeter measuring the current passing between those points can be graduated as a Wattmeter, for the current in ampères multiplied by 100 will give the power in Watts.

In the more general case, however, a special instrument will be required to measure the Watts. The Siemens' Electro-Dynamometer, already described (page 365) can easily be modified for the purpose. All that is required is that the fixed coil, A A (Fig. 190), be wound with fine wire, to serve as a voltmeter, and its ends brought to two binding screws. The ends of the suspended thick wire coil, W W, must be disconnected from A A and brought to another pair of binding screws. If now the ends of A A be connected to the extremities of the part of the circuit in which the power is to be measured, a small current, proportional to the volts, will flow through A A. At the same time the full current is passed through W W, by means of the other pair of binding screws. The readings of the instrument are proportional to the *product* of the currents in the fixed and movable coils. But as one of these currents is the full current, and the other varies as the pressure, the product will be proportional to the Watts, and the instrument may be graduated as a Wattmeter.

Lord Kelvin's current-weigher, or balance, described on page 380, has been modified to act as a Wattmeter. In this case the circuit of the movable coils is distinct from that of the fixed coils, and its ends brought to separate terminals. These movable coils are wound with fine wire, and with additional resistances, if necessary, are placed as a shunt across the points between which the Watts have to be measured, so that the current in them is proportional to the P.D. of that part of the circuit. The full current of the circuit is led through the fixed coils, and as in the previous case the interacting forces will be proportional to the Watts.

The two Wattmeters just referred to are suitable for measuring continuous current circuits only. Wattmeters designed to measure the power given to any part of an alternate current circuit will be described in the next chapter.

The electrical connections of all such electro-magnetic Wattmeters, are depicted diagrammatically in Fig. 211. B and C are the terminals, from which the supply of electric energy is to be drawn, and B D and C F are respectively the positive and negative conductors. One of these (say B D) is cut, and the divided ends brought to the main current terminals, *a b*, of the instrument, so that the whole current passes through the coil A, which, therefore, acts as an ammeter coil. The other terminals, *c d*, are joined, one to the positive lead, B D, and the other to the negative, C F. Inside the instrument these terminals are joined to a fine wire coil, V, which acts as the voltmeter part. Of course, the two coils, A and V, must be so placed that the effect produced depends upon the *product*, and not upon the sum of the currents in them. R is an additional resistance, which in some instruments it may be necessary to add to the voltmeter circuit, in order to better fulfil the conditions for voltmeter working. The current in R is to have no direct effect on the deflection.

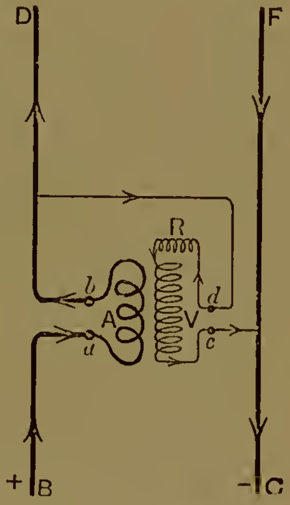

Fig. 211.—Connections of Electro-Magnetic Wattmeter.

Energy.

We now turn to the last and, upon general grounds, the most important of the electrical quantities, the measurement of which we have selected for description. The importance of exact ideas about energy, and, therefore, of its exact measurement, will, we hope, have been sufficiently impressed upon our readers by our preliminary remarks at page 23. And it is not the least interesting or curious of the results of the recent developments of electrical science, that they have led to the direct buying and selling of energy *as* energy, and to the establishment by Act of Parliament of a legal unit for the purchase and sale. For centuries mankind has been in the habit of selling and buying energy indirectly. Thus, when our ancestors, and when we ourselves, bought food, what we really wished to purchase, though we were perhaps unconscious of it, was the energy of the food, which, properly applied, would enable us to go through our daily avocations. Considerations of palatability and the like, though no doubt bulking more largely in our minds, and not unimportant in themselves, were, after all, subservient to the main purpose. Then, again, in purchasing coal or fuel of any kind, what we desire to possess and use is the energy stored up in the fuel, which we transform into heat energy, and use or waste in various ways. In both these cases, however, the thing bought and paid for is not so much *energy*, but so much *mass* of certain materials from which energy can be obtained by certain well-known processes. Of course, it would be much more scientific to pay only for the energy, which is the thing ultimately desired; but we fear that the present state of chemical and physiological science, not to mention the conditions of production and questions of luxury and taste, will not allow us to estimate the value of various foods by specifying their nourishing properties as measured by the amouut of available energy present in them. With regard to coal, the case is different, and large consumers now experiment carefully on the calorific power—that is, the number of available heat-units—of the coal or fuel they use. Still, though this may regulate the price they pay, the thing ultimately invoiced is not so many heat-units, but so many tons (mass) of the fuel. The day is, we fear, far distant when the ordinary domestic consumer will buy his fuel, not by the ton, but by the number of heat-units (which are units of energy) that it will produce.

To understand how energy is bought and sold electrically, we must return for a few moments to the consideration of the units. On page 408 we have defined the Watt, the unit of electrical power, and shown that it is nearly equal to 44¼ foot-lbs. of work per minute. Therefore, if we supply a circuit steadily with so many Watts for a measured number of minutes, the product of the Watts by the minutes and by 44¼ will give us the total number of foot-lbs. of energy supplied. This would not be a convenient method of calculating, because of the awkward constant (44¼) involved, though it would give the result in ordinary engineers' units. It, however, illustrates the principle that to obtain **energy** from **power** we must **multiply** the latter **by time**. In short, since power is the *rate* of doing work, work itself, or energy, must be the product of power by time; just as the total distance travelled steadily by a train is the product of its *rate* of travel by the time taken for the journey.

As the **second** is the electrical unit of time, the energy in electrical units is most simply obtained by multiplying the **Watts** supplied (*i.e.*, the *rate* of supply) by the **time in seconds** during which the rate has been maintained. The result is expressed in units which are known as **Joules**, in honour of Dr. Joule, who experimented so largely on the mechanical equivalent of heat. Thus we have

One Watt × **one second** = **one Joule**.

This unit, however, is much too small for ordinary supply purposes, and consequently the Board of Trade, exercising the powers delegated to it by Parliament, has selected a much larger unit, which is now known as the **supply unit**, and which is the amount of energy supplied when a power of one kilowatt (1,000 Watts) is maintained steadily for one hour. Therefore, to obtain the amount of energy in **supply units** we must multiply the **power measured in kilowatts** by the **time in hours**, for

One kilowatt × one hour = one supply unit.

From these two equations it is easy to see that

One supply unit = 3,600,000 Joules,

since there are 3,600 seconds in one hour.

It is to be regretted that the Board of Trade has not adopted some decimal multiple, say 1,000,000, or, better still, 10,000,000, of the Joule as the unit in which to measure the public supply of electric energy. As it is, with such awkward multipliers as 3,600 being introduced, our electrical units threaten to become as complicated in their relations as the ordinary tables of British weights and measures.

In all the preceding we have supposed that the power is supplied steadily at a definite rate for a certain time. If this be not the case, but if the power fluctuates from time to time, the same *principle* of calculation will hold, the only necessary modification being that the time must be divided up into intervals, during each of which a certain steady rate of supply may be assumed. The energy supplied during each interval must then be obtained by multiplying this rate of supply by the duration of the interval, and finally the total energy will be obtained by summing up the amounts of energy supplied in the various intervals. This method of reaching the final result is known as *integrating*, and may sometimes be followed out by calculation, but is usually much better done, where possible, by appropriate apparatus. Such apparatus we now propose to describe briefly.

Joulemeters.—As with the wattmeters, so with the joulemeters, the conditions to be fulfilled by the instrument are very much simplified if one of the constituents of electrical power—that is, either the pressure or the current—be kept constant. It is then only necessary to take the *time-integral* of the varying constituent, in order to ascertain the energy supplied. By taking the *time-integral*, is simply meant the carrying out of the process of summation indicated in the last paragraph.

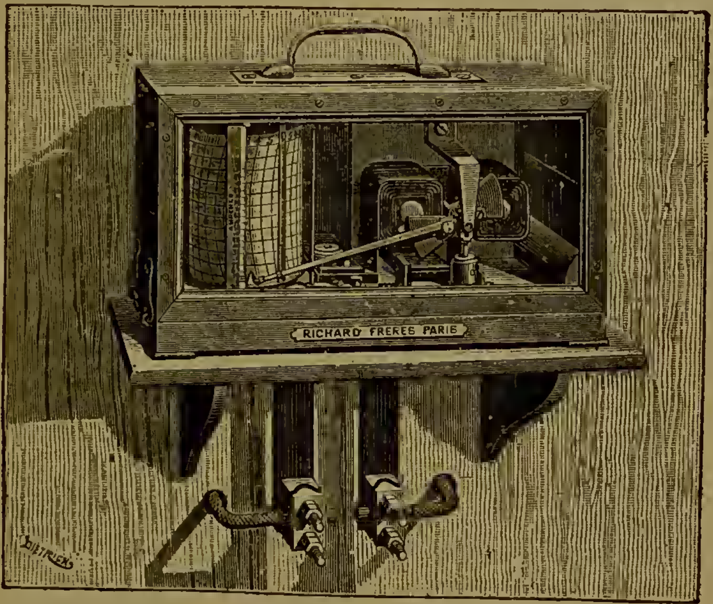

Fig. 212.—Richard's Coulombmeter.

A simple method of taking this time-integral, and one easily understood, is used in the registering voltmeters and ammeters of Messrs. Richard Frères, of Paris. The self-recording ammeter is represented in Fig. 212. The ammeter coils, with the peculiarly shaped movable armature, can be seen on the right. The controlling force which balances the magnetic action of the coils on the armature is gravity. The armature carries a long, light pointer, at the end of which is a pen resting against the cylinder on the left, which is covered with appropriately ruled paper. The cylinder is driven at a definite rate by clockwork, and, therefore, the pen traces a continuous line upon it, the height of which above the zero line depends upon the number of ampères passing through the coil. When the cylinder has travelled nearly once round, the sheet of paper, with its recording line, is removed, and a fresh sheet substituted. In some instruments, instead of this cylinder a band of paper is drawn past the pen at a definite speed. On laying out the used sheet flat, the recording line is seen as an irregular curve, the vertical ordinates, or distances, on the paper, representing current in ampères, and the horizontal distances seconds, or multiples thereof. Areas on the paper, therefore, represent the product of ampères by seconds, that is, coulombs; and by measuring the area below the traced line, or by counting the number of little curvilinear rectangles in that area, the number of coulombs that passed through the coils whilst the line was being traced, can be calculated. If the paper be perfectly uniform in thickness and quality, it is also possible to estimate the coulombs by cutting out the above area and weighing it. A vertical fixed scale is placed just beyond the recording pen, so that the instrument can also be used as an ordinary ammeter.

The coulombs being thus measured, if the supply has been at constant pressure, the product of the coulombs by the volts will give the "joules," and these, divided by 3,600,000, will give the number of Board of Trade units.

Electrolytic Coulombmeters.—Since the measurement of the coulombs can, with a supply at constant P.D., be used to find the total amount of energy supplied, and since the *voltameter* is essentially a coulombmeter (*see* page 305), many attempts have been made to devise a voltameter which can be used for the measurement of the coulombs drawn from a system of public mains by householders. One of these which is very widely used, was designed, and has been brought to great perfection, by Mr. Edison; a recent form of it is shown in Fig. 213. The four bottles in the bottom part of the case are the voltameters, which consist of zinc plates in a solution of sulphate of zinc. The plates are made of pure zinc alloyed with 2 per cent. of mercury, and numerous experiments have shown that such plates, in a solution of pure zinc sulphate, can be relied upon to give an accurate measure of the number of

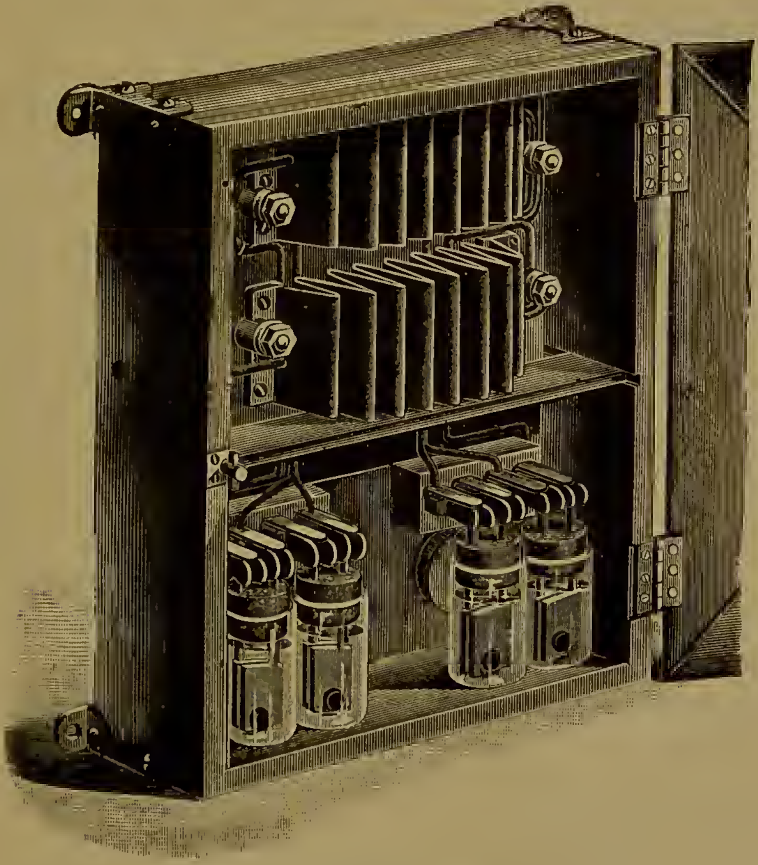

Fig. 213.—Edison's Electrolytic Meter.

coulombs passed. It will be at once obvious that the voltameters shown are much too small to measure the whole current supplied to a house. As a matter of fact, only a small fraction of the current passes through the voltameter, the fraction being so arranged that a deposition of 10 milligrammes of zinc corresponds to 1, 2, 4, or 8 ampère-hours[1] according to the standard pattern of meter used. These numbers correspond to the passage of $\frac{1}{122}$, $\frac{1}{244}$, $\frac{1}{488}$, and $\frac{1}{976}$ of the total current respectively. The full current, except that used for measurement, passes through the zig-zag German-silver resistance seen in the upper compartment of the case, and the voltameter, with an added copper wire resistance, is placed as a shunt across the ends of the German-silver strip. As the temperature varies from summer to winter, the German-silver strip does not change much in resistance, and the usual fall of potential along it is 0·4 of a volt. The resistance of the zinc sulphate solution, however, diminishes with rise of temperature, whilst that of the copper coil increases. Thus, the variation of the resistance of one part of the shunt circuit tends to counterbalance that of the other, with the result that its ratio to that of the resistance of the German-silver strip remains practically constant, and, therefore, the same fraction of the total current is measured in summer and winter. The plates are examined once a month by an inspector from the public supply station; when the proper time arrives the voltameter is carried away, and the change of weight of the kathode plates determined, so that the proper number of coulombs, or of Board of Trade units, may be charged to the consumer.

The meter shown in Fig. 213 is intended for use on the three-wire system, which will be described in the next section. The two strips of German-silver resistance are for use one on the one side, and the other on the other side of the system. In some earlier forms of the meter a glow lamp was placed across the two upper wires, and inserted in the case in winter, to prevent the solutions in the voltameters from freezing. The coulombs passed through this glow lamp were not measured by the voltameters. Though at first sight the necessity for periodical inspection, and the removal of the meter for the purpose of weighing, would seem to entail a considerable increase in the establishment charges of the central station, actual experience shows that when well organised the cost is not heavy. Perhaps a more serious objection is that the consumer has no kind of check on the central station officials, since he cannot be present at the weighings, and has no independent record. This objection is said not to have been found very important in practice, as the consumers are reported to be satisfied that the accounts sent in correctly charge for the energy supplied. A further objection is that the consumer cannot by inspection from day to day ascertain how much energy he is using, and thus keep control over the wastefulness and extravagance of servants and others.

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[1] One *ampère-hour* = 1 *amp.* × 3,600 *seconds* = 3,600 *coulombs.*

Other Forms of Public Supply Meters.—The rapid extension of the supply of electric energy from central stations has rendered urgent the production of a good joulemeter, or *energy-meter*, adapted to the measurement of the actual energy supplied to the consumer, just as a gas-meter is supposed to measure the total quantity of gas delivered. The demand thus created has been responded to by many inventors, and numerous instruments designed to satisfy it have been produced. Of these instruments only two or three can be described here. These are selected from amongst those that have come most widely into use, but there are others, perhaps as widely used, which must be passed by unnoticed. The selection has been made rather with respect to the chief principles utilised being set forth. It may be remarked, in passing, that *the* meter which is to supersede all others, has not yet sufficiently asserted itself, and that it is impossible at the present moment to say which will succeed in the struggle for the "survival of the fittest." In this struggle, provided an instrument be in itself good, business energy and enterprise will tell as much as scientific merit.

From the point of view of the consumer, the conditions to be fulfilled are comparatively simple. Accuracy stands first. Then simplicity or its equivalent, namely, small liability to get out of order. Also it is desirable that the meter should exhibit on a dial, or dials, a record, which can be inspected by the consumer, of the total energy which has been measured up to the time of inspection. Again, no more attention should be required than can be given by periodical visits at long intervals by a skilled inspector from the central station. Lastly, the meter should not consume much energy, as energy so consumed is practically lost, either to the supply company or to the consumer.

The most satisfactory instruments, other things being equal, are obviously those which measure energy directly, and not those which only do this indirectly by measuring one factor (the *coulombs*), and leaving the constancy of the other factor (the *volts*) to chance. The following instruments fulfil this condition.

Aron's Energy Meter.—Many years ago (in 1881), Professors Ayrton and Perry constructed an energy meter, in which the electric energy was measured by the alteration electro-magnetically of the rate of a well-constructed clock. A voltmeter coil of high resistance, placed as a shunt in the circuit, was attached to the end of the pendulum, below which was a stationary ammeter coil carrying the full current. The mutual actions between the currents in the two coils altered the rate at which the pendulum swung by an amount proportional to the product of the two currents, and therefore proportional to the watts under measurement. The swinging of the pendulum added up or integrated all these alterations, and consequently the amount by which the clock went wrong during the whole period dealt with was proportional to the total energy to be measured.

The chief difficulty in carrying out the idea was to get a clock which should go with absolute accuracy when no currents were passing, or at least one which should by itself gain or lose with perfect regularity. Dr. Aron has met this difficulty by using two clocks controlled by two separate pendulums. The ordinary clock face is removed and replaced by a set of counting dials, similar to those used in gas meters. The first of these is so geared to the mechanism of *both* clocks that when the pendulums are swinging synchronously no record is made on the dials; in fact, the clocks are set to work against one another on these recording dials. The pendulums are so adjusted that when there are no currents passing through the meter they keep time with one another, and this condition of no record is attained.

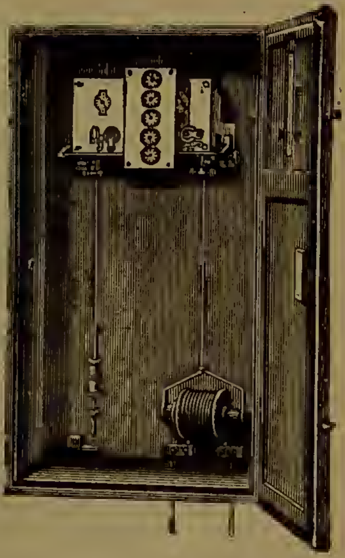

Fig. 214.—Dr. Aron's Energy Meter.

In the meter depicted in Fig. 214 the pendulum of the left-hand clock is an ordinary pendulum, and is unaffected be the currents in the meter. The right-hand pendulum, however, is of very special construction. The bob consists of a horizontal spindle fixed as shown, and carrying a fine wire coil of high resistance, which is placed as a shunt across the terminals of the house, or that part of the circuit the consumption of energy in which has to be measured.

It thus acts as a voltmeter coil, the current in it being proportional to the pressure at these terminals. Surrounding this moving coil, and co-axial with it, is a fixed coil, consisting of a few turns of thick wire, through which the full current supplied is passed. The mutual force between the coils in any position varies as the product of the two currents, one in each coil. But one of these currents consists of the actual ampères supplied, and the other is proportional to the volts; the product is therefore proportional to the volt-ampères or watts. Now, this mutual force alters the time of swing of the right-hand pendulum, and therefore the two pendulums no longer swing in unison. The dials, therefore, begin to record the difference in the swings, which is proportional to the forces called into play on the right-hand side. The actual amount recorded will depend not only on this difference, but also on the total number of swings—that is, on the time. Thus the record is proportional to watts multiplied by time—that is, to energy measured in joules—and by a proper calibration experiment the actual amount of energy, either in joules or Board of Trade units, corresponding to one division on any of the dials, can be ascertained.

A large class of meters are simply small electric motors actuated by the current, and with a counting arrangement to record the total number of revolutions of the armature. The aim is to make the speed of revolution exactly proportional to the power supplied, in which case the total number of revolutions will be proportional to the total energy. One of the simplest and most ingenious of such meters designed by Professor Elihu Thomson, and used largely in the United States, is shown in Fig. 215. The electric motor, which, as explained at page 696, is simply a dynamo worked backwards, consists of a drum armature, M, mounted on a vertical axis, A, and wound with fine wire, which forms part of the shunt or voltmeter circuit of the meter. The current is introduced into the armature in the usual way, by means of the brushes and commutator, and to avoid the uncertainty due to change of permeability in iron, none of this metal is used either in the armature or field-magnet part of the motor. The field magnets are the two large coils which are so prominent in

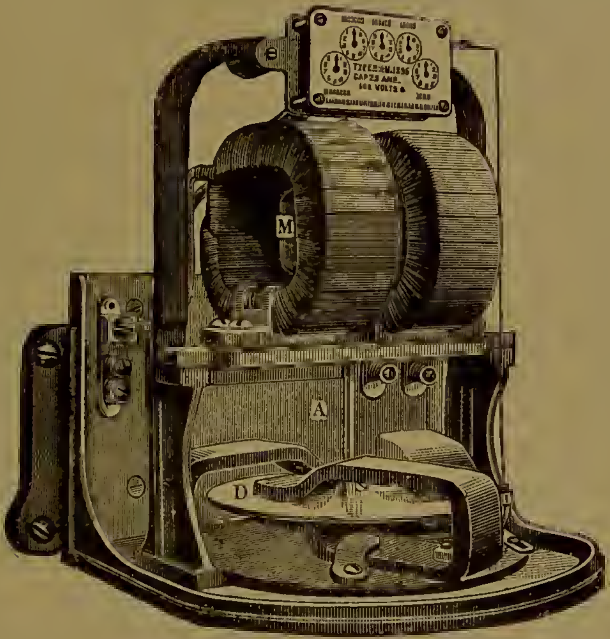

Fig. 215.—Elihu Thomson's Energy Meter.

the figure. These coils carry the full current supplied, and, as there is no iron, produce a field through the armature very accurately proportional to this current. In series with the armature conductor are a few turns of wire on the field magnets; but the greater part of the resistance of the shunt circuit, consists of a non-inductive[1] resistance, the presence of which in the voltmeter circuit enables the meter to be used for alternate, as well as continuous currents.

In the lower part of the meter is the brake, which retards the motion of the armature. It consists of a disc of copper, D, mounted on the same axis, and rotating between the poles of three horse-shoe steel magnets. It is, in fact, an application to a practical purpose of Foucault's experiment, described on page 188. As the disc rotates currents are set up in it which, by Lenz's Law, tend to stop the rotation.

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[1] For the meaning of this term, see p. 450.

The principle on which the motor works is easily understood. When currents are flowing in both the armature and the field magnet coils, the mechanical couple tending to turn the armature is proportional to the product of these currents, that is, to the watts to be metered. The couple, with which the electro-magnetic brake tends to stop the rotation, is directly proportional to the speed, and when the speed becomes uniform these two couples are exactly equal. Thus, for a steady rate of rotation the speed is proportional to the watts, and the number of revolutions has only to be counted to ascertain the total energy. This counting is done by means of a worm on the upper end of the axis, gearing into a toothed wheel which actuates the counting mechanism. The dials can be made to record Board of Trade units (kilowatt-hours) directly, by either moving the magnets of the electro-magnetic brake, or altering the non-inductive resistance.

The above example will give our readers a general idea of the way in which the "electric motor" meters work. The chief difficulty is to so adjust the retarding forces that at all loads the speed shall be strictly proportional to the watts. In the Elihu Thomson meter magnetic friction is used for this purpose. In others some form of fluid friction, either of the air or of liquids, is employed. Another difficulty is to so diminish the solid friction resistances that the meter will run on light loads. For instance, some sixty-lamp meters will not move at all when only one lamp is burning. The subject of alternate-current meters will be briefly referred to in the next chapter.

CHAPTER X.

ALTERNATE CURRENTS.

In the preceding chapters of this section we have endeavoured to set forth, in as simple a form as appears possible, the laws which govern the steady flow of the electric current as a conductor; these laws are the outcome of direct experiment. We have also shown how the laws have led to the elaboration and construction of instruments designed to measure the various quantities involved, whether these be current strength or pressure, or whether they be the still more important physical entities—energy and power. We have purposely refrained from considering the particular cases in which the current is *not* a *steady* one, but has a *fluctuating* or an *oscillatory* character; that is, where the magnitude, or oftentimes both the magnitude and direction of the current are continually changing in a more or less periodic manner. The reason for this course is not that any new principles or laws are involved, other than those to which we have already drawn attention, but because the application of the principles and laws to these cases involves some curious and most interesting consequences, which we think will be more readily appreciated if brought together in one place.

The kinds of fluctuations of currents with which we have to deal, are sometimes divided into two classes. The first is usually referred to as a *pulsating* or *undulatory* current, and is such that, whilst the current is always in the *same direction*, its magnitude varies between certain *maximum and minimum limits*. It may be likened to the flow of blood in the arteries; this flow is always in the same direction, but is alternately quicker as the heart beats and slower in the intervals between the beats; if we were measuring the flow from instant to instant, we should find that it was a *pulsating* flow. Electric currents having the same character are widely employed, more especially in connection with telephony.

The other kind of current fluctuations are those in which the current is alternately in *opposite directions*—that is, it has at one instant a certain maximum value in one direction, and then falls to zero, is reversed, and rises to a corresponding value in the opposite direction, from which it again falls to zero, is again reversed, and rises to its former value in the first direction; these changes being repeated over and over again. Such currents are usually referred to as *oscillatory* or *alternate* currents. The changes which they undergo may be compared with the movements of a pendulum. The central position of the bob is the zero position, or position of rest, and corresponds to the condition of no current; whereas the positions to right and left of it may be regarded as corresponding to currents in opposite directions. Starting from its extreme position on one side, the bob passes through the zero position, rises to the extreme position on the other side, again returns to zero, and rises again to its first position, to repeat these changes over and over again as long as its motion continues. Electric currents having a similar oscillatory character are used in telephony, but have acquired great importance during the last few years in connection with the much heavier work of electrical engineering, more especially in electric lighting and transmission of power.

In what follows we shall not make any distinction between these two classes of fluctuating currents, though our remarks will be more especially applicable to the second class—namely, the "*alternate*" currents. In both cases, however, the additional factor, which causes their behaviour to differ from that of steady currents, is the same; and if we trace out its consequences in one case, there will be little difficulty in foreseeing at least its chief effects in the other. This additional factor is the electric pressure caused by the **self-induction** of the circuit.

Laws of Alternate Currents.

We have already (pages 182 to 185) briefly described what is meant by self-induction, and pointed out its effect when a circuit is made or broken. In each case we found that the self-induction sets up a pressure or an E.M.F. in the circuit which *retards* the change that is taking place. When the circuit is first *made* the self-induction *retards the rise* of the current, and when the circuit is *broken* it *retards the fall* of the current. A moment's consideration will show that the same kind of effects must be produced, not only when the current is made or broken, but also when any change takes place in either its magnitude or direction. For the number of lines of magnetic force which pass through any circuit depends not only on the size and shape of the circuit and the character of the surrounding medium, but also upon the *magnitude of the current* in the circuit. If, therefore, the magnitude of the current be altered in any way, the number of lines passing through the circuit will be changed, and *whilst this alteration is taking place*, the laws of magneto-electric induction (page 174) tell us that there will be *an induced E.M.F.* in the circuit, and that this induced E.M.F. will be such as will *tend to retard* the change which causes it; that is, in this case, the change of current.

The chief peculiarity of self-induction, therefore, is that it only affects the current in a circuit when that current is changing its value. Let it be remembered that this is due to the fact, that with each alteration of current there is an alteration of the amount of *strain-energy stored in the surrounding medium.* Thus, when the current is increased the quantity of energy so stored is increased also, and the increase in the stored energy being obtained from the energy of the current, that current must have less than its final value whilst the process of storing is progressing. On the other hand, when the current is diminished the amount of energy stored in the medium is also diminished, and the difference between the quantities of stored energy belonging to the larger and smaller values of the current is restored to the circuit in the form of current energy which, whilst it is coming in, keeps the current in the circuit above its final value.

Before we proceed to consider special cases, we must explain the meaning of the terms *cyclic* and *periodic*—terms which we shall frequently have to employ. Any set of changes is *cyclic* when the function subjected to change returns after the changes to its initial value or state, so that the net result of the changes, as far as the function considered is concerned, is *nil*. The changes are not only cyclic but *periodic* if, when the function has returned to its first value, these changes are *repeated*, again and again, in precisely the same order. Thus, the motion of a pendulum, or of the fly-wheel of a steam engine, is cyclic and periodic, whilst the motion of a train on the Inner Circle or Underground Railway of London is cyclic but not periodic, because the details of the successive cycles are not precisely similar. In periodic changes the time taken to go through a complete cycle is called the *periodic time*, or, more shortly, the *period*; whilst the number of complete cycles in a given time (for instance, in one second) is known as the *frequency*.

Let us now endeavour to trace the effect of self-induction on a simple circuit, in which the E.M.F. due to external causes is an oscillatory or alternate one, and in which, therefore, the resulting currents have necessarily a similar character.

For this purpose we select the case, already partly considered (*vide* page 193), of a simple loop rotating at a uniform speed in a constant magnetic field. We have previously shown that the E.M.F. induced in this loop can be graphically depicted in a curve which we reproduce here (Fig. 216) with some additions. The points on the line X X′, represent successive instants of *time*, and the *perpendicular* distances of the points on the various curves from this line represent at each instant the values of the quantities to which the curves refer. These quantities have *positive* values (*i.e.*, have a certain direction) for all positions

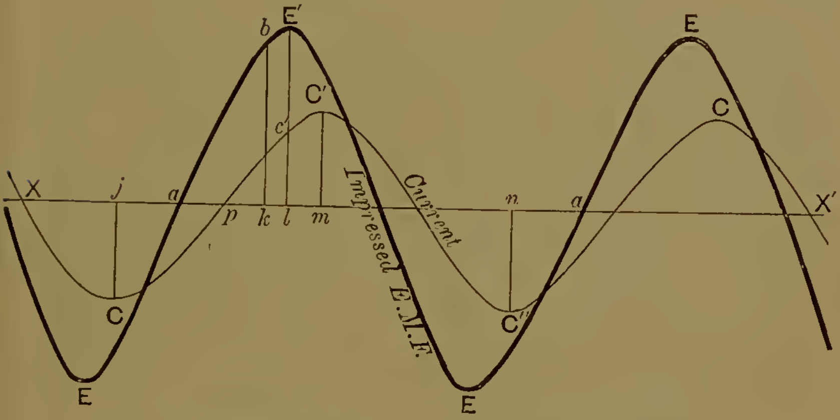

Fig. 216.—Effect of Self-Induction on Current in a Simple Loop.

above X X′, whilst their values are *negative* (*i.e.*, have the opposite direction) for all positions *below* X X′. In all graphic figures of this kind these conventions will be used. The curve, E E′ E, represents the E.M.F. set up in the circuit by magneto-electric induction, as explained at page 195. This we shall briefly refer to as the *impressed E.M.F.* It takes account of all the E.M.F.'s in the circuit, with the exception of those due to self-induction. The corresponding current is shown by the fine-line curve C C′ C″. The scales for the two curves are, of course, different, one being in *volts* and the other in *ampères*.

The first peculiarity that we notice about the current-curve, C C′ C″, is that it *lags behind* the E.M.F. curve. For instance, the maximum value, C′, of the current occurs *later* than the maximum value, E′, of the E.M.F. by the interval of time represented by *l m* on the horizontal scale. A little consideration of the physical changes that are taking place will show why this lagging occurs. During the successive instants preceding the moment represented by *l*, the E.M.F. has been gradually increasing in value from *b k* to E′ *l*. During the same time the current has also been increasing, but at the time *l* has not reached the value corresponding to the E.M.F., E′ *l*, because of the retarding effects of self-induction. The current at the time *l* is *still increasing*, and if the E.M.F. were kept steady at the value, E′ *l* would eventually reach a higher value than *c′ l*, its value at the time, *l*. But after passing *l* the E.M.F. begins to fall off, though it is still in the same direction.[1] The increase of current, therefore, continues, but at a *slower rate* than it would have done had the E.M.F. remained steady; and, therefore, *never reaches the value corresponding*, according to Ohm's law, *to the maximum value*, E′ *l*, *of the E.M.F.* Finally, owing to the falling off of the E.M.F., the current ceases to increase sooner than it would have done, and reaches *its* maximum value at the time *m*, which is necessarily later than the time *l*.

To further assist our readers to understand the effects of self-induction, we have drawn the series of curves in Fig. 217. These curves are all E.M.F. curves. E E′ E is the curve of *impressed* E.M.F., as in Fig. 216. The curve, *c c′ c*, represents the values of the E.M.F. of self-induction. This curve depends upon the *rate of change* of the current, and by comparison with Fig. 216, it will be noticed that it is always negative (*i.e.*, below X X′), whilst the current changes from its maximum negative value, C j (Fig. 216), to its maximum positive value, C′ m, and positive whilst the current is changing from C′ m to C″ n. Also, that the E.M.F. of self-induction is a maximum, $e\,p$, as the current passes through the value zero at p.[1] Finally, the curve, H H′ H, of *effective* E.M.F., is obtained by *algebraically adding* the two curves, E E′ E and $e\,e'\,e$, together. By *algebraically* adding we mean that, wherever the values represented by these two curves are on the *same* side of X X′, they are to be *added* to give the corresponding value of the effective E.M.F., and wherever they are on *opposite* sides of X X′, they are to be *subtracted* from one another, and the value for H H′ H marked on the side of the greatest. An inspection of the figure will show that this has been done.

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[1] In all our diagrams and arguments it must be distinctly understood that we are not referring to the *first* start of the current, but to a time when the impressed E.M.F. has been acting long enough for the current to take a truly *cyclic* and *periodic* character.

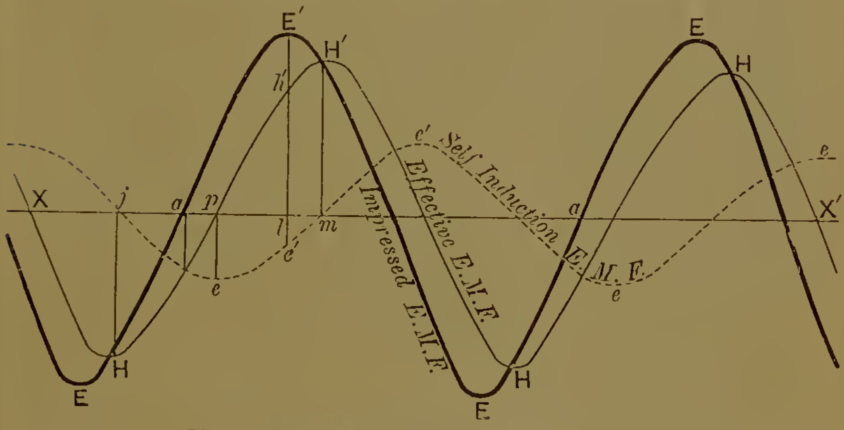

Fig. 217.—Diagram of E.M.F.'s in a Simple Loop.

Returning now to Fig. 216, the values from which the current curve, C C′ C″, is plotted are obtained by dividing the successive values of the effective E.M.F. in the curve, H H′ H, by the resistance of the circuit. In other words, to obtain the current from the E.M.F., Ohm's law must be applied to the *effective* E.M.F., instead of to the *impressed* E.M.F. This is only another way of saying that in applying Ohm's law to a circuit in which the impressed E.M.F. is not steady, the whole of the E.M.F.'s, due to all causes in that circuit, must be taken into account.

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[1] The corresponding letters in the two figures are the same.

There is still another effect of self-induction which has only been incidentally noticed in the foregoing. Not only does the self-induction cause the current curve to *lag* behind the curve of impressed E.M.F., but it also causes the effective E.M.F., and, therefore, the actual current, to have, on the whole, a *less value* than it would have had if there had been no self-induction. Obviously, the mean values of the E.M.F.'s, depicted by the curve, H H′ H, is less than those depicted by the curve, E E′ E. Thus, the effects of self-induction in a circuit, subjected to a fluctuating E.M.F., are two-fold, and may be summarised thus:—*The current lags behind the impressed E.M.F., and its mean value is diminished.* This statement is true, whatever be the kind of fluctuation of the impressed E.M.F.

The above results have been reached by simply considering the problem from the physical side, the graphic diagrams being only given to help the reader to follow mentally the changes taking place. No reference has been made to the numerical calculations involved, nor do we propose to trouble our readers with the details of the mathematical analysis. There are two reasons for omitting these details. In the first place, the mathematics involved are far beyond the plan of this book; and secondly, because modern mathematics are, as yet, only competent to deal with some of the simplest cases that occur in actual work.

Still, it is not impossible to indicate in a simple manner the considerations which influence the magnitude of the various effects. Obviously, one of the chief factors is the numerical magnitude of the self-induction, or as it is more shortly called, the **inductance**, of the circuit. There are several ways of defining this quantity, but for our purpose the following definition will be the most convenient:—*The inductance of any circuit is the ratio of the total number of magnetic lines which the current causes to pass through the circuit to the value of the current*, or:—

$$\text{Inductance} = \frac{\text{Number of Magnetic Lines due to Current.}}{\text{Current.}}$$

If the medium surrounding the circuit be free from magnetic materials, then the above ratio is the same for all values of the current; but if there be masses of iron or other magnetic material near the circuit then the ratio is different for each value of the current, because, as we have already seen, the number of lines set up, in this case, by different currents is not proportional to the current.

In what follows, we shall usually consider the inductance, which we shall denote by the letter "**L**," as constant. If the current be measured in ampères, and the number of magnetic lines be counted in bundles of 1,000 millions (*i.e.*, each bundle of 1,000 millions is to be counted as *one* line only), then the inductance is measured in "**henrys**," a name which has been given to the unit of inductance in honour of Professor Henry, of Princeton, to whose researches we have already (page 182) referred.

The next quantity to which we must draw attention is even more important physically than the inductance, though, as a matter of fact, its value depends on that of the inductance. This quantity is known as the **time-constant** of the circuit, and may be defined as *the ratio of the inductance to the resistance*, or:—

$$\text{The time-constant} = \frac{\text{Inductance}}{\text{Resistance}} = \frac{\mathbf{L}.}{\mathbf{R}.}$$

At first sight it may appear somewhat strange that we should refer to the above ratio as a *time*. To explain this we must remind our readers that we have already pointed out that on first closing any circuit in which there is a steady E.M.F., the current does not at once rise to its full value, given by Ohm's law as $\frac{E}{R}$. Now, both experiment and calculation show that the factor which determines the rate of rise is the above ratio, and that the current actually reaches 36·8 *per cent.* of its final value in the time given by that ratio.

If the inductance be measured in *henrys*, and the resistance in *ohms*, the value of the time-constant is given in *seconds*. The following table gives the value of the time-constant in various pieces of representative apparatus commonly used in electrical work:—

TABLE VIII.—VALUES OF TIME-CONSTANTS.

KIND OF APPARATUS.		TIME-CONSTANT $\left(\frac{L}{R}\right)$ IN SECONDS.
Mirror Galvanometer (5,000 ohms resistance) ...		·0004
Bell Telephone		·001
Electric Trembling Bell		·0048
Telephone Call-Bell (Magneto)		·017
,, Induction Coil	Primary Circuit ...	·0125
	Secondary Circuit ...	·0045
Large Induction Coil (19 in. × 8 in.)	Primary Circuit ...	·09
	Secondary Circuit ...	·065
Telegraphic Relay		·02 to ·05

Since, then, the time-constant is such an important factor on the mere starting of a current in a circuit, it is obvious, from the physical reasons for its existence, that it must also be of importance whenever the current is changing, and that the larger the time-constant, the longer must be the time taken to complete any given change in the value of the current. It is not, therefore, surprising that we find this particular time to be of great importance in all circuits in which the impressed E.M.F. is cyclic and periodic with a very short periodic time (page 428). In all such circuits a complete series of changes have to be completed in a certain time—that is, in the periodic time of the cycle; and it is easy to see that on the ratio between the time-constant and this time must depend the magnitude of the peculiar effects to which we have just drawn attention in our graphic diagrams (Figs. 216 and 217). If, for instance, the time-constant of the circuit be very short compared to the periodic time of a complete cycle of changes in the E.M.F., Ohm's law will be very nearly true at each instant, or there will be very little lag and very little diminution in the effective E.M.F.; in other words, the changes take place so slowly relatively to the time-constant that inductance has very little effect on the result. On the other hand, if the time-constant be large compared with the periodic time, then both the lag and the diminution in the effective E.M.F. may be considerable. Thus, in modern alternate-current dynamos, there are frequently 100 or more complete cycles of E.M.F. per second. If we take the case of 100 complete cycles per second, the periodic time is only $\frac{1}{100}$th of a second, a quantity of the same order of magnitude as the time-constant; thus the above effects may be considerable.

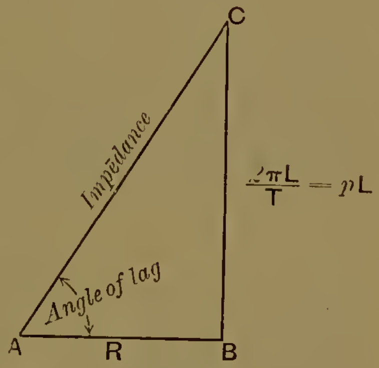

Fig. 218.—Inductance, Impēdance, and Lag.

For the simple case that we have already considered, they may easily be calculated. Let **L** and **R** be respectively the inductance and resistance of the circuit, **t** $(= \frac{L}{R})$, the time-constant of the circuit, and **T** the periodic time of the impressed E.M.F., that is, the time measured by the line *a a*, in Fig. 216. Measure a line, A B (Fig. 218), to represent **R** on some convenient scale; draw B C at right angles to A B, and equal to $\frac{2\pi \mathbf{L}}{\mathbf{T}}$[1] on the same scale. Join A C, then the angle, B A C, is the *angle* of lag, the ratio of which to 360° will be the same as the ratio of the time of *lag* (or, more shortly, the *time-lag*) to the full periodic time. Thus the

$$\text{Time-lag} = \frac{\mathbf{T} \times \text{angle B A C}}{360^\circ}.$$

In order to exhibit the effect on the E.M.F., we shall denote the angle, B A C, by the Greek letter, λ. The value of the *impressed* electromotive force (E) at any time, *t*, may be found from an equation of the form

$$E = E_0 \text{Sine}\, p\, t,$$

where p has the value already given (*see* foot-note), and the value of the *Sine* can be obtained from ordinary trigonometrical tables.

The value of the *effective* E.M.F. is then given by the equation

$$\mathbf{E} = E_0 \text{ Sin } (p\,t - \lambda) \times \frac{\text{A B}}{\text{A C}} = E_0 \text{ Sin } (p\,t - \lambda) \text{ Cos } \lambda,$$

since

$$\text{Cos } \lambda = \frac{\text{A B}}{\text{A C}}$$

The change of the angle from $p\,t$ to $(p\,t - \lambda)$, expresses the fact that there is a *lag* equal to λ, whilst the multiplication by the factor $\frac{\mathrm{A\,B}}{\mathrm{A\,C}}$ (or Cos λ), which is necessarily a proper fraction, expresses the diminution in the *magnitude* of the E.M.F.

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[1] The symbol π represents the ratio of the circumference of a circle to its diameter, and is equal to the number 3·1416; thus 2π is very nearly $= 6\frac{1}{4}$, and B C $= 6\frac{1}{4}\frac{\mathbf{L}}{\mathbf{T}}$ (nearly). If n be the number of periods or alternations per second, then $n = \frac{1}{\mathbf{T}}$; now let $p = \frac{2\pi}{\mathbf{T}} = 2\pi n$, then B C $= p\,\mathbf{L}$.

The current at any time, *t*, can now be found by using Ohm's law; it is :—

$$\mathbf{C}=\frac{\mathbf{E}}{\mathbf{R}}=\frac{\mathrm{E}_0 \operatorname{Sin}(p\,t-\lambda)\operatorname{Cos}\lambda}{\mathbf{R}} \quad . \quad . \quad (1).$$

There is also another way in which the current may be expressed, for, since A B = **R**, we may write the first expression given above for **E** thus :—

$$\mathbf{E}=\mathrm{E}_0 \operatorname{Sin}(p\,t-\lambda)\times\frac{\mathbf{R}}{\mathrm{A\,C}},$$

and then

$$\mathbf{C}=\frac{\mathbf{E}}{\mathbf{R}}=\frac{\mathrm{E}_0 \operatorname{Sin}(p\,t-\lambda)}{\mathrm{A\,C}} \quad . \quad . \quad (2).$$

In this way of expressing the current the length of the line, A C, becomes of such importance that it has been given a special name, and is called the *impēdance* of the circuit. When this denominator is used, the numerator has the same values as the impressed E.M.F., combined with a simple time-lag, and we may write the result in words thus :—

$$\textbf{Current} = \frac{\textbf{Lagged E.M.F.}}{\textbf{Impēdance}} \quad . \quad . \quad (3),$$

a formula which is sometimes referred to as "Ohm's law for Alternate Currents." In using it, it is pointed out that the change in the law involves the introduction of the time-lag into the numerator, and the substitution of the impēdance of the circuit for the resistance. In other words, the cutting down of the current is ascribed to an increase in the effective resistance, or to a kind of spurious resistance, for an inspection of Fig. 218 will show that the impēdance, A C, is always *greater* than the resistance, A B. The excess of impēdance over resistance obviously depends mainly on the values of **L** and **T**, for any increase in the value of **L**, or diminution in the value of **T**, increases the length of B C, and therefore of A B.

The numerical value of the impēdance can be easily calculated by reference to Fig. 218. According to the well-known property of a right-angled triangle, the square upon the slant side is equal to the sum of the squares upon the sides containing the right angle. Therefore

$$\begin{aligned} \mathrm{A\,C}^2 &= \mathrm{A\,B}^2 + \mathrm{B\,C}^2. \\ &= \mathbf{R}^2 + p^2\,\mathbf{L}^2. \end{aligned}$$

The value of the impēdance is, therefore, equal to the *square root* of the right-hand side of this last equation, or, in symbols—

$$\textbf{Impēdance} = \sqrt{\mathbf{R}^2 + p^2\,\mathbf{L}^2}.$$

But this way of regarding the facts is not correct from a physical point of view. Ohm's law in its usual form does not cease to be true for alternate currents. The new factors called into play, as compared with the case of a steady current, bring additional E.M.F.'s into the circuit without affecting the resistance, and the formula used should, therefore, give expression to this fact. This is what is done in formula (1) above, which may be written in words—

$$\textbf{Current} = \frac{\textbf{Lagged E.M.F.}}{\textbf{Resistance}} \times \frac{\mathbf{A\,B}}{\mathbf{A\,C}}.$$

The *general* conclusions arrived at with regard to the effects of self-induction in a circuit subject to an impressed alternate E.M.F., are true, whatever be the character of the cycle of impressed E.M.F., provided only that it be truly *cyclic* and *periodic*. But the *numerical* results given in some of the above equations are only true for the particular impressed E.M.F. specified by the simple curve, E E′ E, in Figs. 216 and 217. When the impressed E.M.F. is of a more complicated character these numerical results are not true, though the general nature of the effects is the same. For instance, if the impressed E.M.F. is represented by the curve given in Fig. 219, we still have a lagging and diminished effective E.M.F.; but it is not possible to calculate the amount of lag, or the factor which determines the diminution. These quantities, if ascertained at all, must be ascertained by experiment.

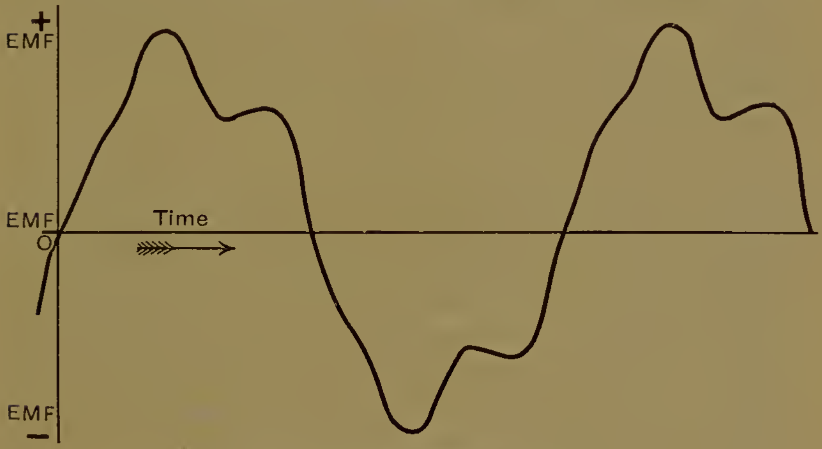

Fig. 219.—Curve of Impressed E.M.F.

We shall now describe a few of the instruments used in alternate-current working. These descriptions will, we hope, bring into prominence, and serve to familiarise our readers with, some of the special peculiarities of alternate electric currents.

Alternate Current Instruments.

(A) **Current Measurers.**—The perfect instrument for the measurement of alternate currents would be one which would faithfully follow every fluctuation of the current, and record it in such a way that the record could be examined and dealt with afterwards. The necessity for the record arises from the fact that in all applications of the alternate current the *frequency* (*see* p. 428) is so great that it is impossible for the eye to follow the changes, even if an instrument existed that would perfectly indicate them. The high frequency, however, has hitherto rendered it impossible to design an instrument having the above properties, and we have, therefore, to fall back upon instruments whose indications depend in some way upon the mean value of the current, and to trust to experiment or theory to enable us to determine from these indications the *true mean value* required.

At the outset, we must exclude all those galvanometers whose indicators are deflected in opposite directions for opposite directions of the current. If such an instrument were placed in an alternate-current circuit, its indicator would probably remain at rest, for all values of the current. For the period of the free swing of the movable system would most likely be many times that of the periodic time of the current, and, therefore, before the system had time to obey an impulse in one direction it would receive an impulse in the opposite direction, and so on continually. The total effect would thus be *nil.*

We must, therefore, fall back upon those galvanometers whose movable system is always deflected in the same direction, whatever be the direction of the current passing through them. They may be divided into two classes. In the first class may be placed those instruments whose indications are strictly *proportional to the square of the current.* We have already pointed out that the square of a quantity is always positive, whether that quantity be positive or negative. If, therefore, the direction of the deflection depends on the square of the current that deflection will always be in one direction, however frequently the current may be reversed. Such an instrument is the Siemens' Electro-Dynamometer, already described on page 365. If one of these be placed in an alternate-current circuit it will give a steady reading as long as the mean value of the current continues the same.

The second class of available instruments contains those in which the movable part affected by the current consists of soft iron, which is therefore magnetised by the current itself. As the magnetisation of this soft iron is reversed when the current is reversed, the direction of the deflection will remain the same. The instruments already described belonging to this class are Ayrton and Perry's Magnifying Spring Ammeter (Fig. 192) and Nalder's Gravity Ammeter (Fig. 194).

The further question of the interpretations of the indications of the instruments of both classes is not a simple one. The calibration, or determination of the currents corresponding to the various readings, is usually effected by means of continuous and steady currents. How the values of the readings are affected by alternate currents depends both on the class of instrument and the character of the alternate current. In instruments of the first class, where the readings depend upon the square of the current, it is easy to see that the reading for an alternate current of a given mean value will be *greater* than the reading corresponding to a continuous current of the same value; for the average value or arithmetical mean of the squares of a series of numbers which follow any regular law is necessarily greater than the square of the average value of the numbers. Take, for instance, the simple numbers

1, 2, 3, 4, 5, 6, 7,

whose average, or mean value, is 4, the square of which is 16. The squares of these numbers are

1, 4, 9, 16, 25, 36, 49;

and the average value of these squares is 20, which is greater than 16. The reason is not far to seek: it is that the larger numbers, when squared, become relatively more important than the smaller numbers.

Now, the values of the forces which determine the readings of the instruments under consideration depend on the squares of the currents, and the average force which determines the actual reading for an alternate current depends, therefore, on the average value of the squares of the currents. Thus, this average force is greater for a given mean value of the alternate current than it is for corresponding continuous current.

How, then, are we to determine the true mean value of the alternate current from the readings of the instrument? The answer depends upon the particular law which expresses the fluctuations of the current. If that law be the simple one graphically represented by the curve C C′ C″, in Fig. 216, theory shows that we must reduce the readings for continuous currents by 10 per cent. In other words, the calibrations for continuous currents must be multiplied by 0·9, in order to give the corresponding calibration for alternate currents following the above law. If the law be more complicated a different multiplier should be used; but in most actual cases the above multiplier is sufficiently accurate.

Instruments of the second class are not so easily dealt with. In the higher parts of the scale it is probable that the above multiplier may be used, and will give fairly accurate results; but in the lower part of the scale, where the period during which the magnetisation of the soft iron is being reversed assumes a relatively greater importance, the correcting factor will probably be different. Such instruments should, therefore, only be used for the higher parts of the scale.

Before leaving this part of the subject we may refer to one interesting structural detail, which must be attended to if any of these continuous-current instruments are to be used for alternate-current work. It is, that all large conducting masses of metal in the base and supporting walls of the instrument should be replaced by non-conducting material. Such masses of metal are unobjectionable in a continuous-current instrument, but if present in an alternate-current one, *may* have currents induced in them by the fluctuations of the current to be measured, and *these induced* currents will lead to a waste of energy, which will show itself in the objectionable form of heat sufficient to make the instrument dangerously hot. Moreover, these induced currents will react on the current to be measured, and may lead to a serious error in the measurement.

(B) Pressure Measurers.—In considering the question of the measurement of alternate *currents*, it will be noticed that the instruments referred to were of the same type and design as some of those already described for continuous-current work. The only difficulty in using these instruments is, as we have seen, that of correctly interpreting the readings; but this difficulty is not an insuperable one. When, however, we turn to the measurement of *pressure*, new complications present themselves. In one sense, all galvanometer voltmeters are available which have the characteristics mentioned on page 440 as necessary in alternate-current ammeters. That is, such instruments, when placed on an alternate-current circuit, would give readable deflections; but the interpretation of the meaning of these deflections is much more difficult than in the case of the ampèremeters.

The difficulty arises from the way in which the instrument is used. It will be remembered that in using high-resistance galvanometers as pressure measurers the galvanometer is placed (page 385) in a branch circuit between the points whose P.D. has to be measured. The current passing along the side branch, multiplied by the resistance of that branch, then gives the required P.D. Such, however, is not the case with alternate currents. On reaching one of the points from which the branch circuit is taken off, the current divides between the two paths, not in the inverse proportion of their *resistances*, but in the inverse proportion of their *impēdances*. Or, to put it more accurately, the *effective* pressure in one path is not the same as the effective pressure in the other path, because of the difference in the value in the two paths of the quantity symbolised by Cos λ at page 436. Thus, to properly interpret the deflections of the voltmeter, the impēdances (or the values of Cos λ) of both paths should be known. This involves a knowledge of the inductances and resistances, as well as the frequency of the alternations; and an alteration in any of these will alter the meaning of the voltmeter deflection. In practice it is impossible to know all these quantities with accuracy, and therefore the employment of a galvanometer as a voltmeter on an alternate-current circuit can only be regarded as a makeshift in the absence of a more suitable instrument.

The solution of the problem of measuring accurately the pressures in an alternate-current circuit, is made possible by the existence of the thermal and the electrostatic instruments to which we have referred at pages 390 and 394. The latter instruments have no self-induction, and very little electrostatic capacity, and therefore their time-constant is inappreciable. At first sight it is not easy to see how they can be adapted for measuring alternate P.D.s, for their deflections depend on the P.D. applied to their terminals, and are therefore reversed when the P.D. is reversed. But in the instrument described on page 398, it will be remembered that the needle, N (Fig. 207), is electrified by being connected to the inside of a Leyden jar, J (Fig. 206), and it is this electrified needle which is repelled by one pair of quadrants and attracted by the other pair. If the electrifications of the quadrants are reversed, so are the attractions and repulsions, provided the electrification of the needle is unchanged. But if, at the moment of reversal of the electrifications of the quadrants, *the electrification of the needle is also reversed*, then the deflection will still be in the same direction as before. To accomplish this the inside of the Leyden jar, J, is connected to the case of the instrument and to the terminal of one pair of quadrants, and thus the *needle* is made to have *the same potential as one pair of quadrants.* Its electrification will therefore change with that of the quadrants to which it is connected, and thus the deflection will always be in the same direction. This manner of using the instrument has been called by Lord Kelvin *idiostatic*, because all the electrifications are produced by the P.D. to be measured. The other method, in which the electrification of the needle is produced by independent means, he calls *heterostatic.*

Unfortunately, when used in this way the ordinary quadrant electrometer is very *unsensitive*—that is, it requires a large P.D. to produce a readable deflection. But the advantages of the method are so great that the problem of increasing the sensitiveness of the instrument is being vigorously attacked at the present time, and several much more sensitive instruments have already been produced.

The only one to which we can refer is Lord Kelvin's *Multicellular Electrostatic Voltmeter*, shown in section in Fig. 220, and in plan in Fig. 221. The changes from the quadrant form of electrometer already referred to are considerable. In the first place, one pair of quadrants has been abolished, the other pair, retained, being represented by C C in Fig. 221, where it will be seen that their shape has been changed from circular to square. In more recent forms of the instrument they have been further changed to a triangular shape. It will be remembered that in the quadrant electrometer each "quadrant" consisted of two horizontal plates, joined by a vertical strip along the circular rim. In the "multicellular" each side, C (Fig. 221), consists of no less than eleven horizontal plates (*p*, *p*, Fig. 220), built up one over the other, so as to form a compound conductor of ten "cells," the plates on both sides being all electrically connected together, but insulated from the rest of the instrument. It is as if we had a whole series of the quadrants of the older instrument piled on top of one another.

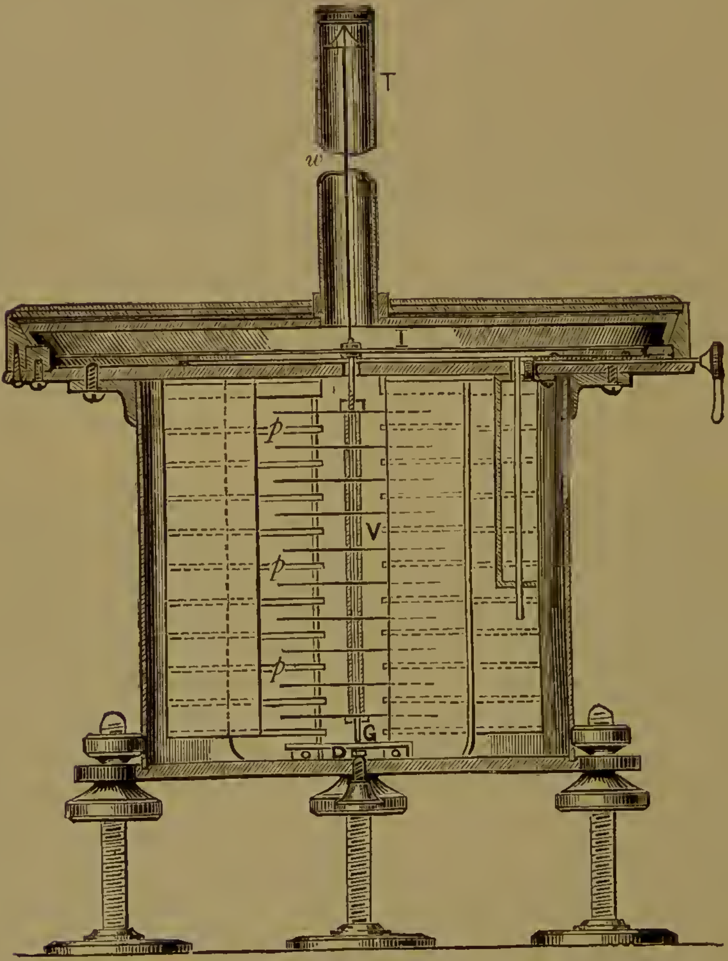

Fig. 220.—Section of Kelvin's Multi-cellular Electrostatic Voltmeter.

This change in the fixed conductors is accompanied by a corresponding change in the movable conductor, which, instead of being made now of a single vane or needle, is built up of ten such vanes, V, attached to a vertical spindle in such a position as to be free to move between the horizontal fixed plates. Thus, when the vanes and fixed plates are brought to different potentials, each vane is acted upon by turning forces due to the plates on either side of it, and, as all the vanes are on one spindle, the total deflecting force is thus made much greater than it would be in a quadrant electrometer for the same potential-difference.

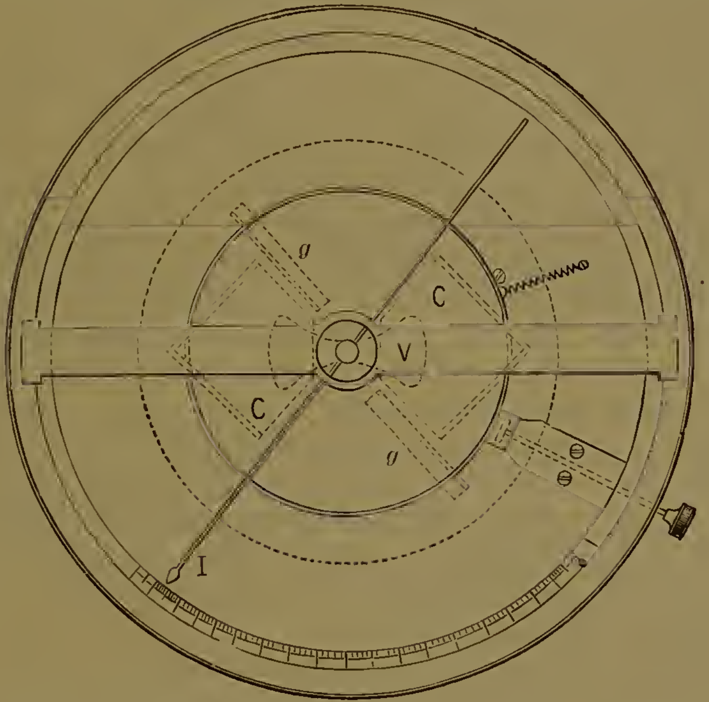

Fig. 221.—Plan of Kelvin's Multi-cellular Electrostatic Voltmeter.

The top end of the spindle carrying the vanes is suspended by a long and fine iridio-platinum (w) wire to a torsion head fixed at the top of the tube T, and thus the controlling force brought into play is that of *unifilar suspension*, which has been already referred to at page 401. Between the lower end of the wire and the spindle there is interposed a fine coach-spring, which prevents a sudden jolt given to the instrument from bringing such a strain upon the fine wire as would probably break it. The torsion head and suspending wire, and therefore the vanes, are not insulated from the body of the instrument. A long aluminium pointer, I, is attached to the spindle, and by its position indicates upon a scale the difference of potential between the fixed and the movable conductors. Two vertical plates, *g g*, are attached to the base of the instrument, to limit the motion of the vanes, V, which, when the pointer is brought to zero by the torsion of the wire, are nearly outside the cells of the fixed conductor and close to these plates. By their repelling action these vertical plates, therefore, produce an initial turning force on the vanes. The lower end of the spindle passes through a guiding hole in a plate, G, attached to these guard plates. The instrument, when used, has to be carefully levelled by means of the three levelling screens upon which it stands, and to assist in this operation a small circular level is permanently fixed inside the shallow box at the top, within which the pointer, I, moves.

Since, whichever of the two sets of conductors is at the higher potential, the vanes, V, tend to move so as to pass within the conductors, C, the deflection of the indicator is always in the same direction, and thus the instrument is available for measuring alternating, as well as steady potential-differences; and, for the reasons already given, is better for the former purpose than any galvanometer form of voltmeter.

The other type of instruments that are available for the measurement of the pressures in an alternate-current circuit are the *thermal voltmeters* of Cardew (page 393) and others.

These instruments, which depend on the heating effect of a current, are unaffected by a change in the direction of the current. Also, they have, as a rule, a very small inductance and a large resistance, so that their time-constant is almost negligible and their impēdance is practically equal to their resistance. The chief objections to the use of galvanometers as voltmeters do not, therefore, apply to the thermal or *hot-wire* voltmeters. These can, therefore, be placed on an alternate-current circuit for the purpose of measuring the mean value of the P.D. between any two points. As regards the interpretation of the meaning of the deflections, the same remarks apply as were made (pages 441 and 442) on the interpretation of the readings of ammeters. That is, if the instrument has been calibrated by using steady P.D.s, the readings must, in most practical cases, be multiplied by 0·9, to give the mean value of the P.D. that is being measured.

Pending the production of a sufficiently sensitive and practical electrostatic voltmeter, hot-wire voltmeters are now being largely used in alternate-current work.

(C) Power Measurers or Wattmeters.—When we pass to the measurement of the power consumed in an alternate-current circuit, we find the same difficulty confronting us in the use of electromagnetic instruments that occurs when a high-resistance galvanometer is employed to measure the P.D. of the circuit. For a reference to the preceding chapter will show that all such electromagnetic instruments for continuous currents consist essentially of two parts combined: namely, an ammeter and a voltmeter part. It is in the latter, because of its high inductance, that the difficulty occurs.

In some of the instruments at present in use an attempt is made to reduce the disturbing factor to a minimum by using only a small part of the high-resistance circuit for the purpose of producing the magnetic effect required, and making the rest of the circuit to consist of a resistance with no, or *inappreciable, inductance.* For the disturbing effect of inductance in any circuit depends upon the ratio of the inductance to the resistance, or, in other words, on the time-constant of the circuit. Thus, in the diagram of Fig. 211, if the resistance, R, be large compared to the resistance of the coil, V, and R be so wound as to have no inductance, then the total inductance of the voltmeter circuit will be small as compared with its resistance, and, therefore, its time-constant will also be small. In this way an attempt is made to cause the disturbing effect of the inductance of the voltmeter circuit to be so small as to be practically negligible. The result can only be accomplished by making the voltmeter part of the instrument very sensitive, for the magnetic effect produced by the coil, V (Fig. 211), depends upon its inductance.

A typical instrument of this class is *Swinburne's Non-Inductive Wattmeter*, the external appearance of which is illustrated in Fig. 222, whilst the working parts, with one of the ammeter coils removed, are shown on a larger scale in Fig. 223. The principle used is the same as that employed in the electro-dynamometer, and depends upon the mutual action between the currents in fixed and movable coils, the magnetic fields produced by which are at right angles to one another. In this case the fixed coils carry the total current of the circuit whose power has to be measured. One of them is shown in position in Fig. 223; they are supported by gun-metal columns from the four little parallel and horizontal pillars on which they slide, and are clamped. The suspended or voltmeter coil, which is quite small, consists of fine wire wound upon a mica cylinder mounted on an ivory spindle. This spindle passes through guides above and below the coil, and is suspended between two fine phosphor-bronze wires top and bottom. The wires are stretched taut, and the upper one is attached to a torsion head carrying an index, which moves over a graduated scale. As in all such instruments, the readings have to be taken when the movable coil is in a zero position. This position is indicated by a pointer moving over the bevelled block at the bottom: the block is illuminated by the lower window, but the position of the pointer is observed through a hole in the upper dial. The angle through which the torsion head has to be turned to bring the pointer to zero is proportional to the watts that are being measured.

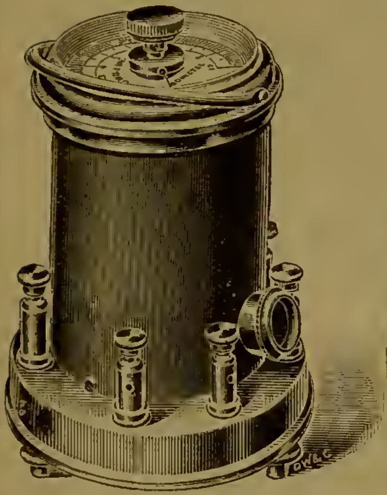

Fig. 222.

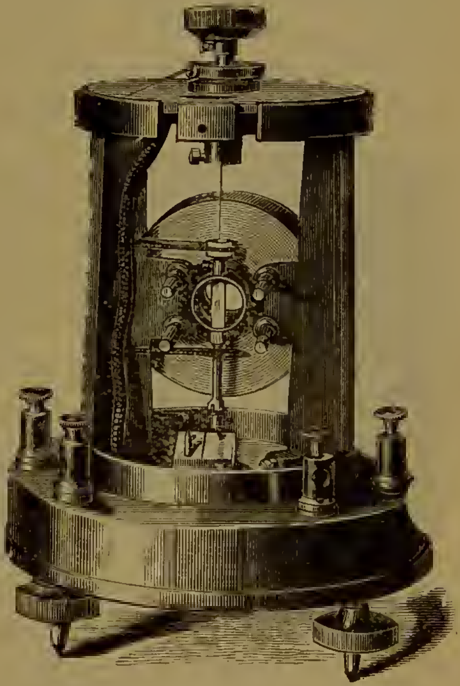

Fig. 223.

Swinburne's Non-Inductive Wattmeter.

As already explained, a resistance, R (Fig. 211), is put in series with the movable coil. For low pressures this resistance is carried in the base, but for high pressures, such as 2,000 volts, R has to have a value of about 80,000 ohms, and the coils are placed in a separate box. With these resistances it is claimed that the time-constant of the voltmeter circuit is practically negligible.

In Fig. 224 there is depicted diagrammatically an ingenious method of measuring the power of an alternate-current circuit without employing any voltmeter coils at all, and therefore avoiding the difficulties due to their inductance. It depends upon the simultaneous observations of three electro-dynamometers used as ammeters, and is a modification by Dr. Fleming of a similar method due to Professor Ayrton and Dr. Sumpner, in which three voltmeters were employed. The circuit in which the power has to be measured is represented by *a b*, and a_1, a_2 and a_3 are the ammeters. Of these a_1 has passing through it the currents in the circuit *a b*; a_2 is traversed by the currents in a shunt circuit, *c d*, made up of a non-inductive resistance, *r*, of known value in series with a_2; and a_3 takes the whole of the currents passing through both circuits. In these circumstances it can be shown mathematically that the watts, W, used in the circuit, *a b*, are given by the formula

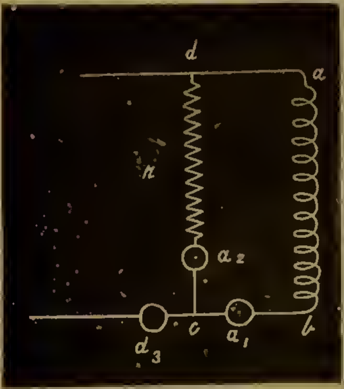

Fig. 224.—Measurement of Alternate-Current Power.

$$W = \frac{r}{2} (A_3^2 - A_1^2 - A_2^2),$$

where A_1, A_2, and A_3 are the readings expressed in ampères of the three instruments, and *r* is the value of the non-inductive resistance. Unfortunately, to obtain good results the current in *c d* has to be comparable with that in *a b*, and thus the method leads to an appreciable loss of energy.

Other methods have been devised for overcoming the difficulties of measuring power used with alternate currents, but a description of them would lead us far beyond the plan of this work.

(D) Public Supply Instruments.—Considering the importance and extent of the various alternate-current supply stations that are now delivering energy by means of such currents to the general public, doubtless more interest attaches to the instruments used to measure the energy so supplied, than to the alternate-current instruments already described. And this interest is fully justified on purely scientific grounds, for several of the instruments that have been designed for this purpose exhibit beautiful applications of some of the less generally understood electrical laws to practical purposes of measurement, and by studying the details of their construction a fresh and charmed insight is gained into the nature of the laws themselves. We therefore need not apologise for devoting a short space to the description of one or two such instruments, widely differing in their details and method of working.

The great difficulty in designing a satisfactory alternate-current energy meter is that already alluded to in speaking of the corresponding wattmeters—namely, the inductance of the pressure part of the instrument, where that part acts electro-magnetically. For it will be remembered that an "Energy-Meter" is simply an integrating wattmeter. On account of this difficulty some of the meters used are simply *coulombmeters*, and the consumer has to trust to the supply company to keep the pressure constant, and so ensure a fair calculation of the total energy supplied.

The Elihu-Thomson meter, already described when dealing with continuous-current meters, is one which is capable of measuring alternate-current as well as continuous-current energy. This is because the pressure or voltmeter circuit through the armature has its impedance very nearly equal to its resistance, a result partly due to the absence of iron, and partly to the insertion of a large non-inductive resistance in series with the inductive resistance of the armature itself. The calibration of the instrument is, therefore, very little affected by a change in the frequency of the currents, though it will be remembered[1] that the frequency affects the impēdance.

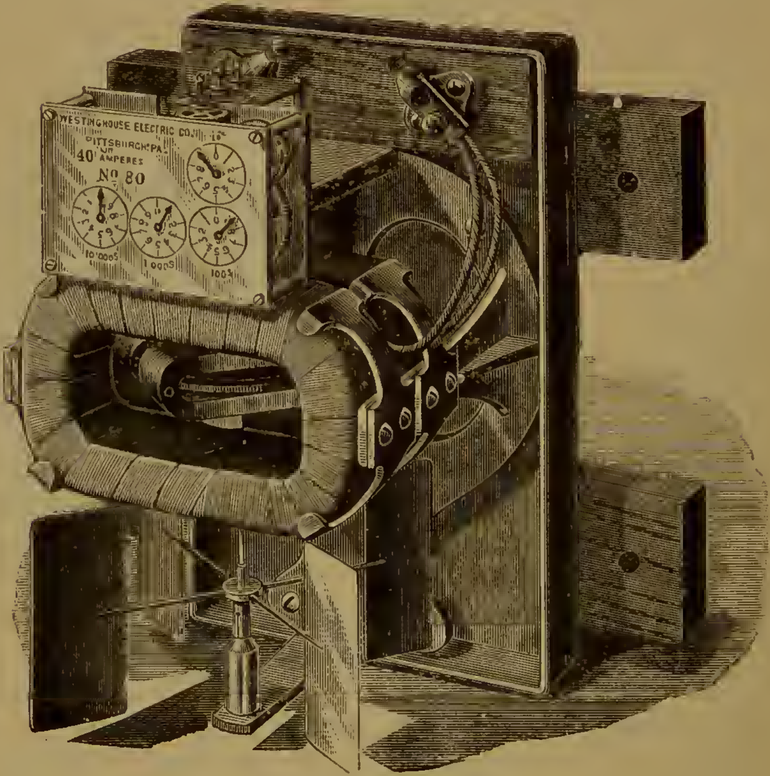

Fig. 225.—Interior of Shallenberger's Meter.

The next meter to which we shall refer can only be used with alternate currents, as its working depends upon those properties of such currents which distinguish them from continuous currents. It is, in fact, a small alternate-current motor, with its speed suitably controlled, and so far resembles the Elihu-Thomson meter, from which, however, it completely differs in all the essential details of its construction and mode of action. The meter is known as the "Shallenberger Meter," having been designed by Mr. O. B. Shallenberger, the electrician to the Westinghouse Company of Pittsburg, Pennsylvania. We shall first describe its construction, and then explain its mode of action somewhat minutely, as the explanation will be of assistance to us later on, in considering alternate-current motors.

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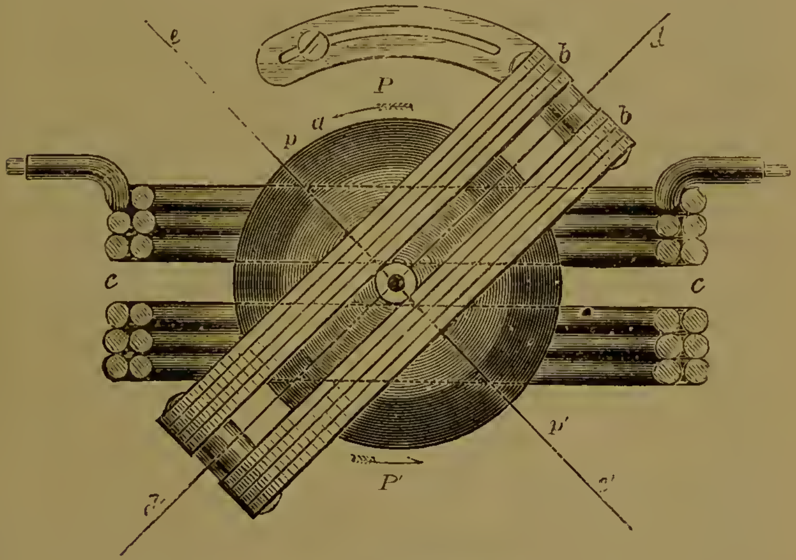
[1] See page 458.



F 226.—Electrical Circuits of Shallenberger's Meter.

The internal appearance of the meter, with the protecting case removed, is shown in Fig. 225. At the top is an ordinary set of counting dials, which register by means of a worm, gearing into the first wheel of a train, the total number of revolutions of a vertical spindle set in motion by the action of the current that has to be integrated. Beside this worm, the spindle, which is very carefully mounted on hardened and polished pivots, carries only the four light aluminum vanes seen at the lower part of the figure, and the light wrought-iron disc, *a*, shown more clearly in Fig. 226, which represents the electrical parts of the instrument. These last consist of the two thick wire coils, *cc*, which carry the total current passing to the consumer. Inside these coils are the coils, *b b*, of approximately rectangular shape, and closely encircling the disc without touching it. The coils, *b b*, consist of simple flat copper strips forming closed circuits, and placed side by side; they are usually set with their axis at about 45° to the axis of the coils, *c c*, but this angle is capable of adjustment, and the instrument is calibrated by altering it until a known current gives the required number of revolutions per minute.

To understand why the disc, *a*, rotates when an alternate-current is passed through the coils, *c c*, we must carefully consider the consequences of the laws of electro-magnetic action and induction already explained. In the first place, a great number of the lines of force due to any current in the coil, *c c*, will pass through the coil, *b b*. As the currents, *c c*, are rapidly reversed, the number of lines of force due to them which pass through *b b* will be continually changing, and therefore, since the coils, *b b*, formed closed circuits, there will be currents induced in them of the same frequency as the currents in the coils, *c c*. But the E.M.F.'s induced in *b b*, depend on the *rate* of change of the currents in *c c*, and as this rate of change is greatest when the currents are zero, and is nought when the currents have their maximum positive and negative values, it is obvious that the induced E.M.F.'s lag a quarter of a period in phase behind the currents in *cc*. As *b b* is not without inductance, the currents therein lag a little behind the impressed E.M.F.'s, and therefore are rather more than a quarter of a period behind the currents in *c c*.

Next consider the resultant magnetic field, as represented by the poles which these joint currents set up in the disc, *a*. As it will not affect the general result, we shall, for simplicity, suppose the currents in *b b* to be exactly a quarter-period behind those in *c c*. The current in *c c*, if acting alone, would produce poles in the disc at P and P′, increasing, diminishing, and changing sign exactly in time with the changes in the current. Similarly the currents in *b b* alone would produce similarly changing poles at *p* and *p*′. The joint effect is easily seen, if we remember that when *c c* produces its maximum poles at P and P′ there is no current in *b b*, and therefore no poles at *p* and *p*′, and *vice versâ*. Thus at one instant there is an effective north-seeking pole at P; a quarter of a period later there is an effective north-seeking pole at *p*; a quarter of a period later this pole has moved round to P′; and a quarter of a period still later is at *p*′; and so on. At intermediate instants the effective north-seeking pole is in intermediate positions. The general effect, then, is that we have a *rotating magnetic field*, which, if the disc were held fast, would produce poles in it rotating in the direction of the arrow.

To understand how this rotating field causes the disc to rotate, we must remember that the disc is a conducting mass forming innumerable possible closed circuits in all directions, through which the lines of force of the rotating field must successively pass. In these circuits, therefore, E.M.F.'s will be set up, producing swirls of current, which lag a little bit in phase behind them. On this slight lag depends the whole action, for the effective field gets a little in front, in a position to attract the circuit carrying the current which it has just set up, and thus the disc follows the rotating field round.

We have already, in connection with the Elihu Thomson meter, dwelt fully upon the necessity, in a motor meter, for balancing the turning torque due to the electro-magnetic actions, by an equal frictional torque, so that the speed may be perfectly steady for a given current. In the Shallenberger meter, the turning torque is proportional to the square of the current, and as the speed of rotation must vary directly as the current, the friction break must set up a retarding force proportional to the square of the speed. The meter, as shown in Fig. 225, is covered by a close-fitting case, and the aluminium vanes, fixed on the lower part of the spindle, churn the air in the lower part of this case, thus setting up the required retarding force.

Polyphase Alternate Currents.

One of the greatest disadvantages of the ordinary, or, as it may be called, the *single phase*, alternate current is that, up to the present, it has not been found possible to re-convert its energy back again into mechanical energy in an efficient and satisfactory manner. Wherever power is to be used for either lighting or heating purposes, ordinary alternate currents are of great service in transmitting it economically over long distances, but when the power is required at the distant end in the form of ordinary mechanical power for driving machinery, these currents have hitherto been almost useless. This is owing to the fact that a thoroughly satisfactory electric *motor*, or machine for converting electric into mechanical power, has not yet been devised for use with ordinary alternate currents. Such motors, however, have been successfully employed on a large scale with alternate currents of a peculiar kind, known as polyphase currents, the nature and production of which we propose to explain briefly.

In the electric transmission of power by ordinary alternate currents two conductors are used, and at any instant the current in one of these is exactly opposite in *phase* to the current in the other. By this we mean that the current in, say, the outgoing line, reaches its *positive* maximum at the same instant that the current in the return line reaches its *negative* maximum. The fraction of the full periodic time which measures the interval intervening between the instants at which currents of the same period successively reach their positive maxima, expresses the *difference of phase* between them. In the case just cited this difference of phase is half a period, and the currents are said to be in *opposite phases.* But if, for example, the periodic time be $\frac{1}{100}$th of a second, and one current reaches its positive maximum $\frac{1}{300}$th of a second after another, its phase is said to be one-third of a period behind the first.

Now, it is possible to transmit power electrically by means of alternate currents differing in phase by any simple fraction of a period, provided a sufficient number of conductors be used. Thus, if the phases differ by one-fifth of a period, five lines must be used, and so on. Such currents are called *polyphase currents.* A multiplication of the number of lines has obvious disadvantages, and, therefore, at present, only three lines are used, and the currents in these differ by one-third of a period. Thus, at a certain instant, one line would be carrying a positive current, equal in magnitude to the sum of two negative currents in the other lines. An instant later the first and second line would both be carrying positive currents, equal in sum to a single negative current in the third line, and so forth. The condition is that the *algebraic* sum of the currents in the three lines should always be equal to zero. In what follows we shall confine ourselves to this case of three currents differing in phase by one-third of a period, and therefore known as *three-phase* currents.

A little consideration of the laws of magneto-electric induction will show that it is quite easy to generate three-phase currents. Let A, B, and C, Figs. 227 and 228 be three exactly similar coils, equidistant from one another on the ring armature of a two-pole dynamo. For a moment suppose each coil to be disconnected from the other and closed on itself. As the ring rotates alternate E.M.F.'s and the corresponding currents will be set up in these coils, and it is quite easy to see that the E.M.F.'s will reach their positive maxima at successive moments of time, separated by intervals equal to one-third of the time taken by the ring to make a complete revolution—that is, one-third of the time of a complete alternation of each E.M.F. These induced E.M.F.'s therefore *differ in phase* by one-third of a period. The arrow heads are intended to represent the directions of the E.M.F.'s at the instant considered, the rotation of the ring being clockwise. Thus in A the E.M.F. is increasing, in B it is diminishing, but is in the same direction as in A, whilst in C it is also diminishing, but is in the opposite direction to what it is in A and B.

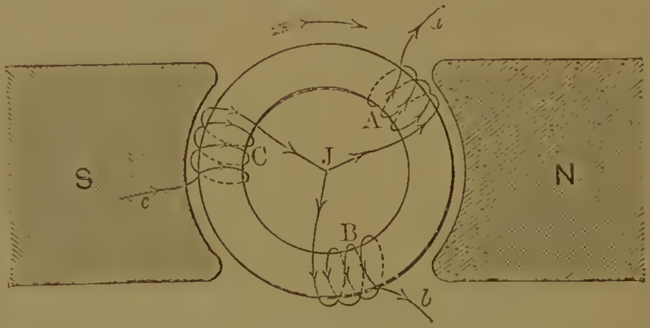


Fig. 227.—"Star" Connections of Three-Phase Alternator.

There are several ways in which these induced E.M.F.'s may be made to supply currents to external circuits, and two of these are represented in the diagrams. In Fig. 227 what has been called the "Star" method of connection is used. The three corresponding ends of the coils are connected together at a common junction, J, and the three other ends, *a*, *b*, and *c*, are brought to three insulated rings on the axle of the machine, from which sliding brushes carry the current to the line wires, which in their turn have a common junction in the distant apparatus. At the instant represented currents are going out from a and b, whose sum is equal in magnitude to the return current entering at c.

In Fig. 228 the "Mesh" method of connection is represented. Here one end of each coil is connected to the beginning of the next, as in the ordinary Gramme ring; but the points a, b, and c, instead of being joined to the segments of a three-part commutator, are joined to insulated collecting rings, from which, as in the "star" method, three-phase currents can be supplied to three separate line wires. At the instant represented the current going out from a will be equal to the sum of the currents in x and y, and intermediate between them in phase. The current from b will be equal to the difference of the currents in z and y, whilst the current entering at c will be equal to the sum of the currents in x and z. As before, in the outer wires, the current coming to c is equal to the sum of those going from a and b.

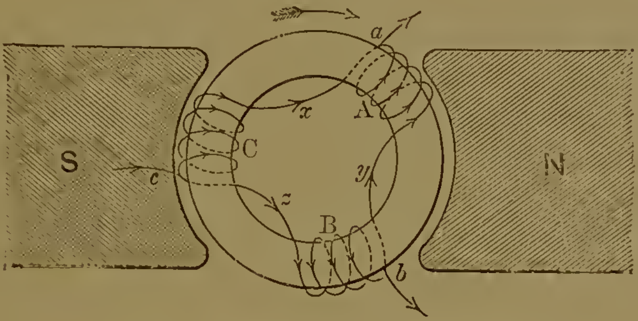


Fig. 228.—"Mesh" Connections of Three-Phase Alternator.

In the preceding section of this book we have given details of so many alternators, that it is perhaps not necessary to describe a three-phase machine. Such machines are usually multipolar, and their armature coils are simply divided into three sets, so placed relatively to the poles that the E.M.F.'s induced in them differ by one-third of a period.

One end of each set of coils is brought to a collecting ring, and the other ends are joined up inside the machine according to either the "star" or "mesh" methods explained above, or in one of the other more complicated ways theoretically possible.

Electric Waves.

Before closing this chapter a brief reference may be made to a subject which has excited great interest during the last few years, not only in the scientific world but also amongst that large section of the general public which keeps more or less in touch with the scientific progress of the time; a subject, moreover, which has largely modified our views of the *modus operandi* of electric phenomena, and holds out promises of still further advance in the not distant future.

In the preceding chapters attention has been drawn repeatedly to the necessity of examining the actions taking place in the surrounding media, instead of confining the attention to the conductors, and the whole trend of recent theory and research has been in the direction of amplifying our knowledge of those actions.

Two kinds of strain energy existing in the medium have been referred to; one very fully, the other briefly. The first is the magnetic energy in the medium surrounding a conductor in which a current is flowing, the other (page 396) is the electrostatic strain energy which exists in the dielectric that separates two conductors at different potentials. If the current in the one case or the P.D. in the other be steadily maintained the magnetic or the electrostatic field is quite steady. But consider what must happen whilst this state of strain in either case is being set up. The energy stored in the medium when the steady state is reached must travel from the source of energy to its final position through the medium in a kind of pulse or wave, which must take time to reach its destination by a continuous path; at least this seems the only way in which our finite intelligence can even vaguely attempt to follow what is taking place.

To simplify the case, let us consider only the magnetic field due to a current, as being the one with which we have most familiarised our readers, merely remarking that corresponding consideration will apply to the electrostatic field, and indeed that both fields are to be regarded as simultaneously present. The above-mentioned propagation of the energy of the field must take place during its setting up. But what happens when the current is stopped? We have seen that much of the energy is thrown back into the circuit and retards the fall of the current, and therefore the energy once more travels through the medium. But all of it may not reach the original circuit, for, as we have seen, part of it may set up currents in neighbouring circuits, and thus be, as it were, intercepted by them.

Pass now from a single make and break of a current in a circuit to the fluctuations of an alternate current and still consider the magnetic field only. This field must be in a continual state of flux, growing, diminishing, reversing, and so forth. The disturbances which produce these changes, and which we may certainly call *electric*, must be travelling through the medium from their source, and must take time to travel from point to point. Moreover, as we have seen, and as we shall see more forcibly in treating the alternate current transformer, much of the energy from the current generators may appear in distant circuits which have no conductive connection with the circuit of the generator.

Two questions may here be fairly asked. If the above disturbances travel through the medium, do they travel at a definite speed, and has that speed been measured? The answer is "yes" to both questions. There are several indirect ways in which the speed of propagation of an electric disturbance in air can be measured, and these were very fully elaborated by Clerk-Maxwell in his classical book on

Electricity and Magnetism. The result of the measurements is that in all cases the speed so nearly approximates to that of light that no reasonable doubt can exist of the identity of these two speeds.

The velocity of light in air is about 180,000 miles, or one thousand million feet per second. A frequency of 200 oscillations per second is rather above than under that of the alternate currents in modern alternators. If we suppose the disturbances set up in the medium by these currents to be propagated in the form of waves with the above velocity, then each wave must be about 900 (*i.e.* $\frac{180000}{200}$) miles long from crest to crest. It is obvious that we cannot test our supposition by looking experimentally for the ordinary phenomena of wave motion in waves of this unmanageable length. For these tests we must obtain waves of much shorter length, or, what is the same thing, instead of the oscillations being a few hundreds per second, they must be many millions, for with one million oscillations per second the waves would still be about one thousand feet long.

Electric Oscillations.—Forty years ago Lord Kelvin, then Professor Thomson, showed that theoretically the discharge of a Leyden jar, as ordinarily taken, does not consist of a single current in one direction, but of rapid oscillations of current, dying away in much the same manner as the vibrations of a bell. The frequency and the periodic time of the oscillations were shown to depend upon the electrostatic capacity of the jar and the resistance and inductance of the discharging circuit; *i.e.*, upon the electrical time-constants involved. These theoretical deductions were afterwards conclusively verified experimentally. In ordinary cases the frequency is high, mounting up into millions per second, so that we have in the disturbances set up in the surrounding medium an opportunity of testing whether the propagation is of the nature of wave motion.

Hertz' Experiments.—There still remained the difficulty of how to detect the existence of the waves experimentally, and this was not overcome until quite recently (in 1887) by Hertz, whose early death we have so lately been called upon to deplore. Using the principle of resonance, so well-known in acoustics, he showed that very simple apparatus only was necessary for quite a number of experiments, and with this he conclusively proved that waves were set up in the medium by the discharging Leyden jars. All the phenomena characteristic of waves —such as reflection, refraction, polarisation, and so forth— were produced and examined. Since Hertz' first papers on this subject appeared, numerous workers have attacked the problems presented, and many other ways of detecting the waves have been elaborated, in addition to the original Hertzian Resonators. The description of these is beyond the scope of this book, but some of the curious properties of the waves themselves may be mentioned. First, there is no breach of continuity in the series of wave-lengths which can be obtained. Waves varying in length from a minute fraction of an inch to miles have been produced. Still more curious is their behaviour as regards ordinary material objects. To most of these waves stone and brick walls and partitions, pitch, wood, and many ordinarily opaque objects are *perfectly transparent.* Waves generated outside a building can be picked up inside, and *vice-versâ;* they can pass from one room to the next though ordinary means of communication are carefully closed. In fact, the only class of substances opaque to them are the good electrical conductors; and the more perfect the conductor the more *opaque* is it to the electric waves.

Electro-Magnetic Theory of Light.—In his great work, already referred to, Clerk-Maxwell put forward tentatively the theory that light is an electro-magnetic phenomenon. The chief basis of the theory was the experimental identity of the two speeds, but other considerations were adduced. Even before Hertz' experiments, most scientists who had carefully considered Maxwell's theory had little, if any, doubt that he was right. But Hertz' and subsequent experiments have conclusively proved the practical identity of light, so-called radiant heat, and the electric waves we have just been considering. The mode of vibration and the speed of propagation *in vacuo* are the same, the only differences are those of wave-length and frequency. The eye, in fact, is an electric organ, but, whether fortunately or unfortunately, it would be perhaps rash to say, its range is very limited. Out of the myriads of actually existing and possible frequencies, it can only recognise those lying within about a single octave ranging from about 380 to about 760 billions of vibrations per second. The sense of heat covers a wider range, but is not so sensitive or definite in its indications. Outside these senses, though literally immersed in the waves, we are quite unconscious of their existence, and the methods of detecting them that we have alluded to must be ranked amongst the greatest discoveries of the last quarter of the nineteenth century.

One word more and we must leave this fascinating subject. It is well-known that in the science of optics it has been found necessary to postulate the existence of a medium, called the "ether," for the transmission of the wave-motion which is now universally recognised as constituting light. This medium, in order to satisfy the experimental conditions, must have properties which it is very difficult to realise as being possessed by so subtle a body. On the other hand, we have the mysterious entity, which since the time of Gilbert has been called Electricity. What is it? We do not know. But a consideration of the experiments and phenomena, so briefly referred to above, has led more than one thinker on the subject to put forward, at least tentatively, the theory that *Electricity* and the *Luminiferous Ether* are identical.

Part III.

THE APPLICATIONS OF THE ELECTRIC CURRENT.

CHAPTER XI.

APPLICATIONS OF THE CHEMICAL EFFECT.

THE next aspect in which we wish to present the Electric Current to our readers is one which deals with those applications by which the labours of scientists and the ingenuity of inventors have captured and harnessed it for the service of mankind. We have already remarked in the early part of this book, that in the vast majority of the applications of electricity to practical work, it is the energy of the Electric *Current* that is the working vehicle, and not those other manifestations of electrical activity which are familiar on the lecture table and in the laboratory. These latter are of extreme interest in all speculations regarding the nature of the entity that we call electricity, and did space permit we should be only too glad to refer to them in detail. As it is we have elected to confine ourselves to Current phenomena, feeling that, without making the book too bulky, our limits are all too small to do adequate justice even to these.

In dealing with the applications of the Electric Current, we shall first take up separately the special applications of each of the three characteristic effects, and then in a final chapter deal with the question of the Electrical Transmission of Power, in which advantage is taken, as necessity suggests, of any one or more of these effects.

In considering the production and the laws of the electric current, we have in each case taken up the chemical side of the subject before either the thermal or the magnetic. We therefore propose to follow the same course in this section, although the applications of the chemical effect are neither, on the one hand, so imposing or gorgeous as those of the thermal effect, nor, on the other hand, so far-reaching in their social consequences as those of the magnetic effect. Nevertheless, they have a certain interest of their own, and have not been without their influence in cultivating the artistic tastes of the people, by bringing faithful reproductions of works of art within the means of those who have no opportunity of becoming familiar with the originals. Lately, too, these chemical effects have been, and still are being, further developed in directions which promise to have important bearings on more than one industry. As usual, we begin with a brief historical sketch.

Historical.—The discovery of the chemical effect of the current has already been alluded to (page 15). Very shortly afterwards, in 1801, Wollaston observed the deposition of copper on a silver coin, connected with a more positive metal and dipped into a solution of copper sulphate. Still more striking were the experiments of Brugnatelli, at Paris, in 1805, in which, for the first time, a base metal was coated with a more costly one, a process which is now extensively employed under the name of *electro-plating*. Brugnatelli, using an ammoniacal solution of chloride of gold and a Volta's pile, succeeded in gilding silver coins. The process of electro-plating was not, however, commercially developed until 1840, when Messrs. Elkington, of Birmingham, took out patents in England and France for various practical processes. The chief difficulties of previous workers had been sometimes the crystalline nature and sometimes the non-adhesive and non-coherent character of the deposits. The successful deposition of iron was not accomplished until 1846, when Boettger discovered the secret; and a good method of steel-plating was only discovered in 1859, by Jacquin.

Meanwhile, another branch of the art, that of *electrotyping*, had been receiving attention. De La Rue, in 1836, had noticed that the copper deposited on the negative plate of a Daniell's cell could be detached, and that this copper bore the *most exact* impress of the surface on which it had been deposited. In 1839 three different experimenters simultaneously developed practical methods for applying this discovery to the copying of medals, or other small objects. These experimenters were Thomas Spencer, of Liverpool, who brought the process most rapidly to perfection; Professor Jacobi, of St. Petersburg, who used it for copying engraved copper plates; and C. J. Jordan, a printer, of London. The process of copying medals and coins soon became a fashionable amusement. The coin to be copied was varnished on one side, to prevent deposition there, and was made the negative plate of a short-circuited Daniell cell; in the course of a few hours a thick deposit was formed on the exposed side, and could easily be removed. The copy was, of course, in intaglio, instead of in relief, and another copy would have to be taken from this to reproduce the original coin.

The necessity for using *two* electrical processes in order to obtain a fac-simile copy of the original was obviated by a discovery of Murray, in 1840. He found that a mould taken from the original coin in any convenient material, such as wax or plaster-of-Paris, could be rendered sufficiently conductive on the surface by coating it with plumbago or blacklead. The mould so coated can be used to receive the deposition, which then forms a faithful reproduction of the original.

It is interesting to note that one of the earliest continuous-current dynamos, Woolrich's (page 225), was constructed for the purpose of supplying current for electroplating. In fact, this was the first occasion on which the dynamo was used for commercial purposes.

In the following account of the applications of the chemical effect of the current, we first describe the processes involving the electro-deposition of *metals* in the several industries of electro-plating, electro-typing, and electro-metallurgy, and then deal briefly with other applications usually classified under the general heading of electro-chemistry. These include bleaching, tanning, dyeing, rectifying alcohol, etc., by means of the current, as well as electric analysis, and a few other applications.

Electro-Plating.

Simple as is the theory of the process of electro-plating, there is scarcely any operation in the applications of science which requires greater care to carry it to a successful issue. It is essentially a case where proper attention to minute details makes all the difference between success and failure.

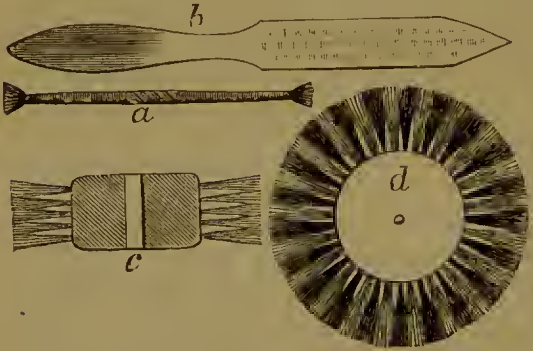


Fig. 229.—Electro-plater's Brushes.

Perfect cleanliness, as regards the surfaces to be coated, is absolutely necessary. The articles to be plated are first, if very dirty, mechanically cleaned by means of a "scratch brush," *c d* (Fig. 229), which is a circular brush of fine brass wires mounted on a leather spindle, and rotated at a high speed. For smaller articles other forms, *a*, *b*, of brushes are used. After the mechanical cleansing, grease and fat are removed by dipping in hot caustic potash, after which the objects are dipped in some kind of acid bath, whose composition and strength depend on the material of the object. They are then ready for the plating bath.

Any electric-current generator may be used, provided it supplies currents of not too high a voltage, and of a proper magnitude for the work. In the simplest case a galvanic generator and the depositing cell may be combined, as described in our historical notes. Such an arrangement for copper depositing is shown in Fig. 230. A number of porous pots are arranged round the depositing vat, which is filled with a solution of sulphate of copper. These porous pots contain dilute sulphuric acid, and in each is placed a cylinder of zinc; all these cylinders are connected electrically by a circular metal wire, on which rest two stout cross wires, from which the object to be coated is suspended. If the object be non-metallic, for instance a plaster-figure, its surface must be rendered conductive by being coated with a layer of plumbago. The arrangement is essentially a Daniell's battery, with the object to be plated forming the negative plate.

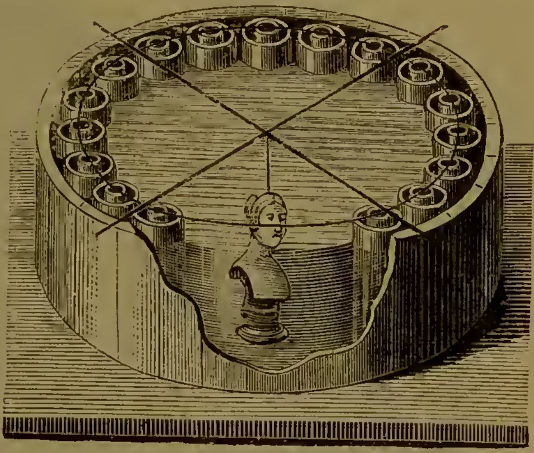


Fig. 230.—Combined Battery and Plating Apparatus.

For good work, and especially where the objects to be plated are numerous, it is best to separate the current generator from the plating bath. A convenient form of plating bath is shown in Fig. 231. The plating solution is contained in a rectangular tank, round the rim of which run two stout copper wires or bars, one inside the other. Either the outer one is raised, or the inner one is on a sunk ledge, so that a metal rod placed across the outer rectangle clears the inner one without touching it. In the figure the outer rectangle is to be connected to the positive terminal of the source of electric currents by means of the binding screw

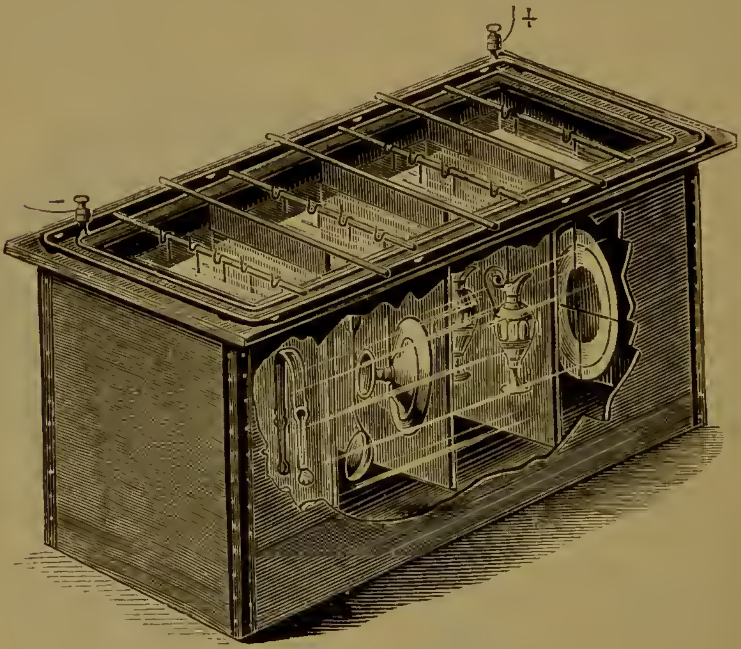


Fig. 231.—Electro-plating Bath.

marked +, whilst the inner rectangle is to be connected to the negative terminal by the binding screw marked –. Proper switches and adjustable resistances are, of course, placed in the circuit to control and regulate the current. An ampère-meter should also be in circuit. The articles that are to be plated, when properly prepared, are hung in the solution from short metal rods, which just bridge the inner rectangle, whilst from the longer rods bridging the outer rectangle, are hung the *anodes*, usually rough plates of the metal that is being deposited. The current enters the solution by these anodes (which are dissolved by the chemical actions caused by the current), and leaves by the objects which form the kathodes, and upon which, therefore, the metal of the solution is deposited. The amount of current passing at any time must be proportioned to the surface of the objects to be coated, as too dense a current will cause a bad deposit, whilst if the current is too small, although the deposit will be good, it will take too long to attain the required thickness.

For gold-plating an alkaline bath of gold chloride and potassium cyanide is used, and the colour of the deposit is improved by warming the bath. A silver bath consists of silver cyanide and potassium cyanide, whilst for copper a solution of copper sulphate is used. In nickel-plating a double sulphate of nickel and ammonium is employed. The character of the deposit depends greatly on the exact composition of the bath, as well as on the current density. Numerous recipes for baths of various kinds of deposition are given in special books on the subject.

After the deposition of the desired thickness of metal, the object has usually to be again scratch-brushed and afterwards burnished to give it a bright metallic appearance.

As a source of current for electro-chemical work, the dynamo has now almost completely displaced the galvanic battery. The class of dynamo required is one giving a large current at a low pressure, unless a good many baths are placed in series, when a higher total pressure may be used. The disadvantage of joining baths in series is that the same amount of chemical action must be going on simultaneously in each, and therefore the work must be carefully distributed amongst them.

Most ordinary dynamos can be modified so as to be suitable for electro-deposition, the chief change being that the wires on the armature and field magnets, though occupying about the same total space for the same output in watts, must be much thicker, and therefore less numerous than for lighting purposes. The change in the number of the wires will lead to the generation of a lower E.M.F., and the increase in their size will enable them to carry a heavier current without dangerous heating. One other change is necessary; the commutator having to pass a larger current must be made longer and more massive.

The dynamos used for electro deposition should always be shunt wound, lest the back E.M.F. of the baths should temporarily exceed the forward E.M.F. of the dynamo, and lead to a reversal of the magnetism of the latter. The same considerations apply to dynamos used for charging secondary batteries, in connection with which (page 529) we shall discuss them more fully.

Electro-Typing.

The general nature of the process of electro-typing, or the reproduction electrically of exact fac-similes of objects, has been described in our historical notes (page 469). First a mould, or matrix, of the object to be reproduced is taken. For this purpose several materials are available, such as lead, fusible alloys, sealing-wax, bees'-wax, gutta-percha, plaster-of-Paris, etc. When large objects have to be copied, the casts of different parts are taken separately, and afterwards fastened together. If the surface to be copied is very much under-cut, gelatine is used, as it is sufficiently elastic when set to allow of the removal of the object, and to afterwards regain the form given to it by the surface from which it has been removed.

After the mould has been taken it is prepared for the bath by coating its surface with a film of metal or plumbago. If the surface be porous it must first be made smooth by dipping in molten wax or stearine. The best plumbago is used, and is applied carefully with a camel's hair brush, until the surface is evenly and smoothly covered.

The process of reproducing a statuette is shown in Fig. 232, where one half of the mould, originally taken in two parts, is removed to show the arrangement. In a case of this kind the anode should have approximately the shape of the mould, to ensure an even deposition on all parts. For this purpose platinum wire, bent to the required shape, is introduced into the interior of the mould. The platinum is connected to the positive supply main through *a* and K, whilst the conducting plumbago surface of the mould is connected to the negative main through *k*, *c*, and Z.

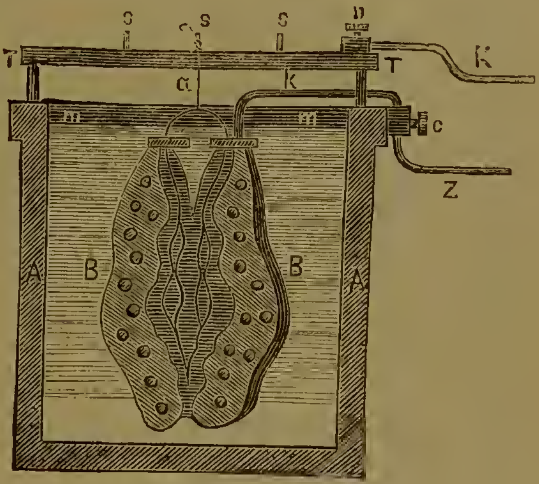


Fig 232.—Electro-typing a Statuette.

One of the most important of the applications of electro-typing is to the reproduction of fac-similes of engravings and letter-press type for printing purposes. With regard to the former, the practice of printing from the original block or plate has been entirely superseded where large numbers of copies are required, by printing from copper electro-types deposited on moulds taken from the original block. As this block has only to make impressions on the soft material of the moulds, its sharpness and clearness is indefinitely preserved. When it is remembered that each mould furnishes a copper electrotype, from which a great number of copies can be printed before it becomes blurred, we see that the production of what are practically proof engravings, or equal thereto, has been widely extended. Thus it is stated that one wood-block for the engraved heading of the *Times* newspaper, was the parent of no less than 20,000,000 impressions before it required renewal.

With regard to letterpress printing, the electro-type enters into competition with the stereo-type, and for many classes of work, especially in the United States, has completely displaced the older method. One of the objects of both methods is to enable the original type to be set free for further use, instead of being kept standing. The electro- or stereo-type plates can also be stored against the contingency of more printed copies being wanted, a process that could not be followed with ordinary type without sinking a large amount of capital. Lastly, the expensive ordinary type being only used to take a few proof copies, lasts much longer, and can be used many more times than would otherwise be possible.

The process of taking one of these electro-types is, in its main outlines, the same as that described for the production of the fac-simile of a medal. Bees' or other wax is usually employed for the material of the mould. A good plane surface of wax having been made, it and the surface of the type are both carefully plumbagoed. They are then pressed together in a hydraulic or other press, and the wax surface when separated shows an excellent impression, reversed, of course, of the type. After being carefully examined and touched up, the surface of the wax is again plumbagoed, or otherwise rendered conductive. Copper wires are then embedded in the side of the mould, and contact made between them and the conductive surface.

The mould is now ready for the depositing vat, in which it is kept until a sufficient thickness of copper has been deposited. It is then taken out, and the wax removed, leaving a thin copper "shell," which is afterwards "backed" with about an eighth of an inch thickness of stereo-type metal. These are afterwards sometimes further mounted on blocks of hard wood.

The process of taking electrotypes of engravings is essentially the same as that just described, the chief difference being that gutta-percha is preferred to bees-wax for the mould.

Electro-Metallurgy.

The chemical effect of the current can also be used for metallurgical purposes, such as the production of pure metals from impure solutions of their ores, for the refining of impure metals, and also for the accurate assay of certain ores, more especially copper ore.

The electrolytic refining of copper is carried out on a fairly large scale in various parts of Europe and America. The impure copper treated is in the form of "Chili bars," "black copper," "copper matte," "pimple copper," etc. This impure copper is cast into convenient sizes and shapes for anodes, which are hung in the depositing vats. These latter are usually placed in series, so that dynamos of higher E.M.F. may be used, thus diminishing the cost of the conductors for carrying the large currents employed. In some American refineries a different arrangement is used. Plates of the impure copper are placed successively in the vat with one thin plate of pure copper at one end. The latter is connected to the negative main, and the first of the impure plates to the positive main. The current thus passes all the plates one after the other, and each of the intermediate plates is both a kathode and an anode, receiving pure copper on one side, and having impure copper dissolved off on the other. The P.D. required in a vat with a kathode of pure copper and an anode of copper pyrites is about 0·75 volt, but is much lower if the anode be simply some form of impure copper. For very good results, *i.e.*, to obtain very pure copper, the deposition must proceed very slowly, and in some cases the increase of thickness of the kathodes is only allowed to be $\frac{1}{25}$th of an inch per week of 156 hours. A fairly safe density of current is five ampères per square foot at the kathodes. With rapid deposition some of the metals present as impurities may be deposited on the kathode. The metals which are so deposited most readily are silver, bismuth, antimony, arsenic, and tin.

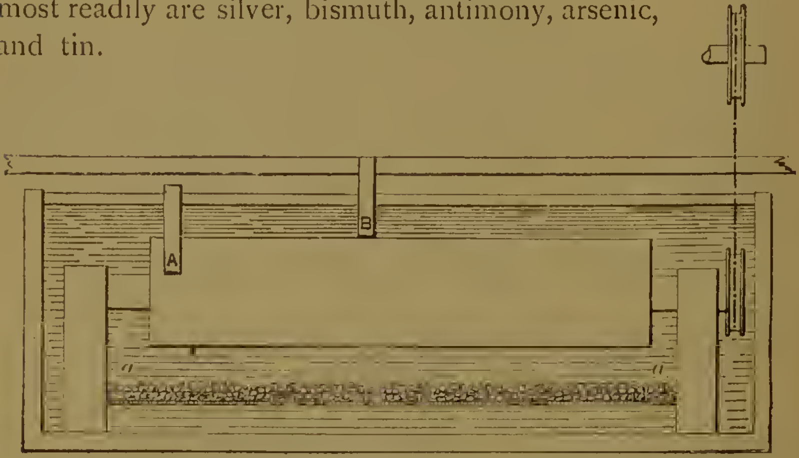


Fig. 233.—Elmore Depositing Tank.

The plant required for a large electrolytic copper refinery is very extensive, and involves the sinking of a large amount of capital. This necessarily results from the slowness with which deposition must proceed at any individual kathode, thus requiring the laying down of a large number of depositing tanks if a large quantity of copper is required per week. For instance, it has been estimated that from £45,000 to £50,000 capital is required for a refinery capable of turning out about 500 tons of refined copper per month.

During the last few years a process of copper refining, called from the name of its inventor the "Elmore" process, has been vigorously pushed. It is at present specially devoted to the production of copper tubes, and the coating of iron tubes and hydraulic rams, etc., with copper. The special feature of the process is that the copper is burnished with an agate burnisher whilst being deposited. A section of one of the depositing tanks is shown in Fig. 233. The tank is of wood, lined with bituminous material, and filled with sulphate of copper. The anode consists of granulated copper, lying on a tray, *a*, *a*, near the bottom of the tank. This granulated copper is produced by melting Chili bars, and pouring the molten copper into water. For the production of tubes the kathode consists of a carefully turned iron mandril, mounted on glass bearings, and kept slowly rotating by the simple chain gear at the right-hand end. The ends of the mandril are coated with non-conducting varnish, to prevent deposition on them. As the mandril rotates copper is deposited on it, the current being led off by the brush, A. Simultaneously the burnisher, B, which is faced with agate, is pressed against the mandril by rubber bands, and slowly travels from end to end continually, backwards and forwards. When the required thickness has been deposited, the mandril and its covering are taken to the machine room, and the mandril removed by a mechanical process.

The great advantage of the burnisher seems to be that with it at work a much greater current density can be employed without the deposit being crystalline and weak. Thus the current used may be as high as fifteen or twenty ampères per square foot, which will deposit a thickness of one-eighth of an inch in six days of twenty-four hours each. This rapid deposition considerably diminishes the amount of capital invested in copper "lying idle" in the factory. As the granulated copper contains 97 per cent. of pure copper the risk of the deposition of impurities is minimised. Not only is the copper deposited very pure, but it has great tensile strength, and will stand considerable extension without breaking.

One of the depositing rooms in the German Elmore works, about forty miles from Cologne, is shown in Fig. 234. With the exception of the special machinery, which is not very prominent, for rotating the mandrils and moving the burnishers, the figure gives a very good idea of the appearance of the depositing rooms in any large refinery. In this room there are forty tanks in series, each requiring a P.D. of rather less than one volt, and capable of depositing from six to seven tons of metal per week. The power for driving the dynamos is obtained from turbines worked by water from the Sieg, an affluent of the Rhine. Eventually eight large dynamos, capable of producing currents of the aggregate value of about 10,000 ampères at 50 volts, are to be employed in the factory.

With this we leave electro-metallurgy for the present. There are, however, still other branches in which the heating effect of the current is employed; to these we shall return in the next chapter.

Electro-Chemistry.

Although, strictly speaking, the last three sections are all branches of electro-chemistry, we prefer to reserve the term for those less important applications of the chemical effect, which are unconnected with the great metal industries of the country. Amongst these we may enumerate bleaching, dyeing, tanning, the rectification of alcohol, the purification of sewage, and some minor applications.

Electric bleaching and the electric production of bleaching powder, are subjects which have recently attracted a great deal of attention from inventors and manufacturers. In most bleaching processes chlorine is the active agent. It is usually obtained from chloride of lime and bleaching powder, a substance which is manufactured for the purpose

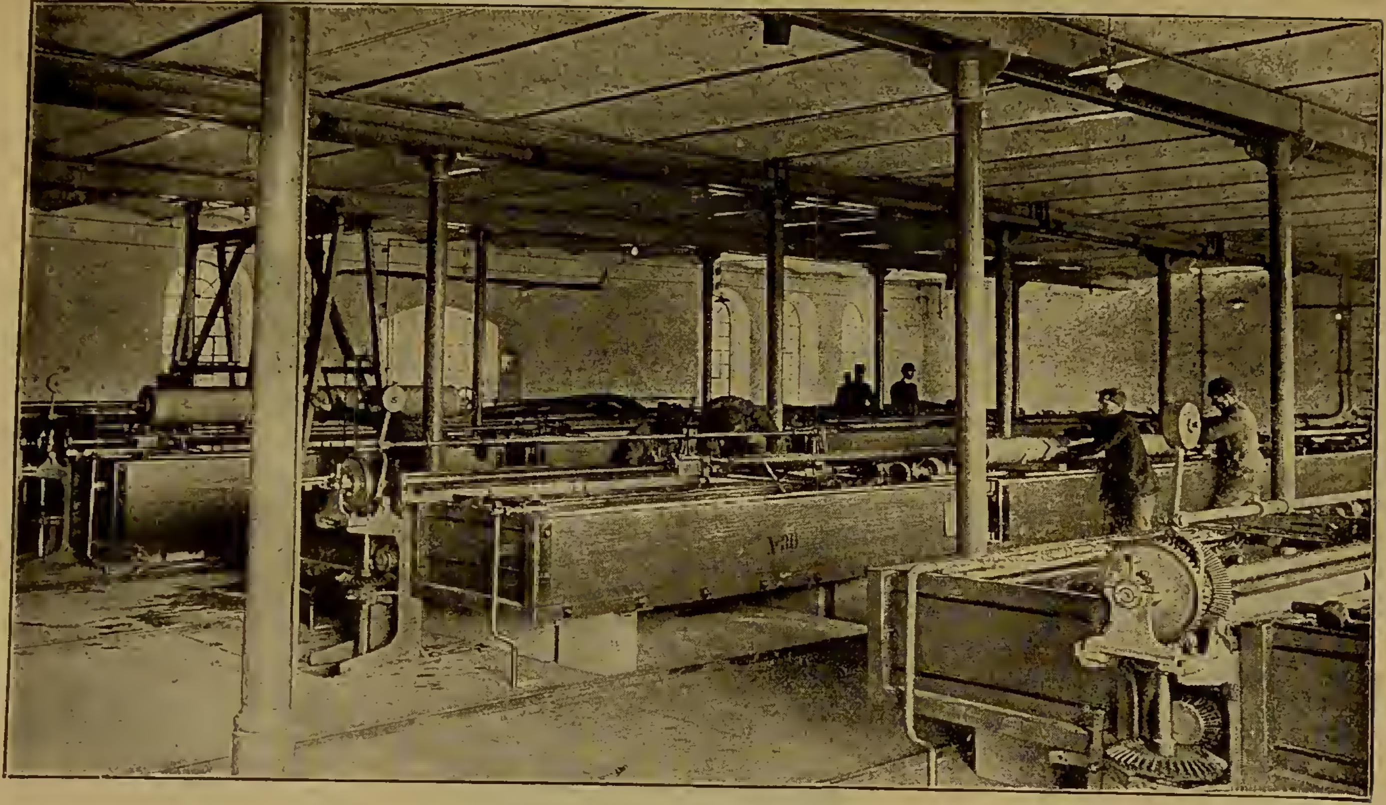


FIG. 234.—DEPOSITING-ROOM IN ELMORE WORKS.

in large quantities. Electrically, two general methods have been developed. In one the attention is directed to forming bleaching powder, or some substitute more economically than in the ordinary way, whilst in the other the electric current is applied in the operation of bleaching itself, and the attempt is made to dispense with the use of bleaching powder. The subject is an extensive one, but for illustration a description of a process of the first kind may suffice.

Following a long series of investigators, this process has been developed on a commercial scale by M. Hermite. It consists essentially of the electrolysis of magnesium chloride in a basic solution, whereby a liquid of high bleaching power is produced. This liquid is at once used for bleaching purposes, and when spent is returned to the electrolysers to be regenerated. Thus the same molecules of chlorine are used over and over again for bleaching.

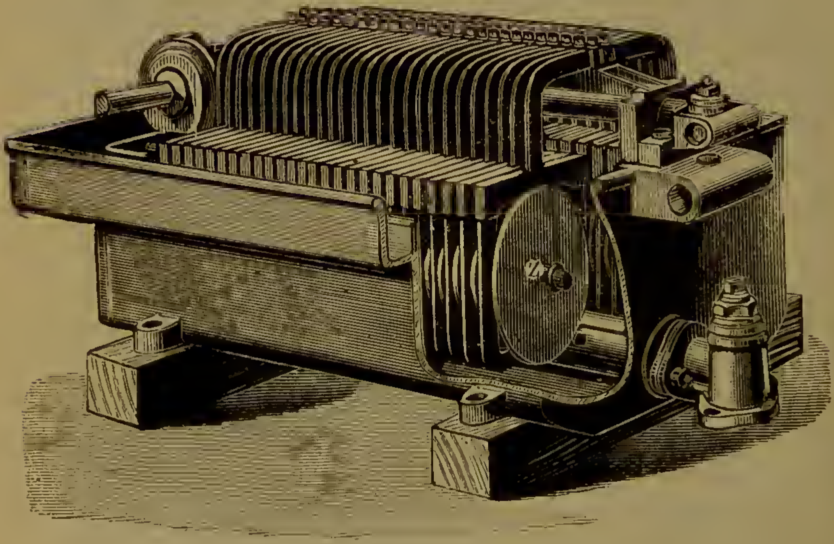


Fig. 235.—Hermite Electrolyser.

M. Hermite's electrolyser is shown in Fig. 235. It consists of a galvanised cast-iron tank, in which are arranged a great number of electrodes. The kathodes are circular zinc discs Z, mounted at regular intervals on two slowly rotating spindles. Interlaced with these discs, without touching them, are the anodes, one of which is shown separately in Fig. 236. It consists of an ebonite frame, F F, on which is mounted platinum gauze connected by a leaden lug to a substantial copper bar, by which the current is led in. On the anode is an ebonite scraper, S, which reaches across to the neighbouring cathode, and scrapes off any deposit as the zinc disc slowly revolves past it. The anodes and kathodes are connected in parallel circuit, so that the total current supplied is divided amongst them. In the bottom of the tank is a large pipe with numerous holes, by which the liquid to be treated enters the tank. After passing the electrodes the liquid overflows into the ledge or gutter round the top edge, whence it is pumped to the bleaching vats.

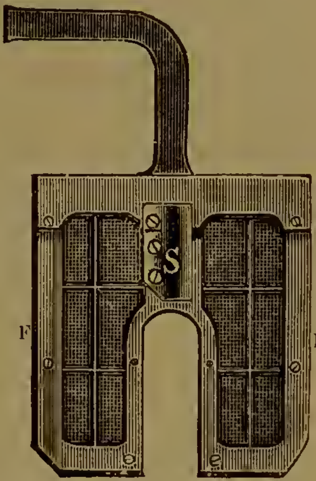


Fig. 236.—Anode of Electrolyser.

The solution used contains five per cent. of magnesium chloride and five per cent. of sea-salt, together with a small quantity of recently precipitated magnesia. Chlorine is liberated at the anode, and hydrogen at the cathode. These primary products of electrolysis react, on the chemicals present, and produce a solution of great bleaching power, which is at once led off to the bleaching vats and used. The back E.M.F.'s in the electrolysers are high, requiring, with the resistance to be overcome, a P.D. of five volts, at which pressure a current of 1,000 to 1,200 ampères is used.

In *electric-dyeing*, which is especially applicable to the dyes procured from coal-tar, the colouring matter is formed in the places where it is required by electrolytic action. The material is saturated with a dilute solution of the proper aniline salt, and is placed on a metal plate, on which the pattern to be formed has been traced, and the parts of the plate where there is to be no action covered with non-conducting varnish. The plate is connected to the positive or negative terminal of a battery, according as oxidation or reduction is required, and in about a minute the operation is complete. For other purposes other methods are employed.

The electric current is also used to accelerate the process of tanning. In the old process the hides to be tanned had to be kept in the tanning liquor for long periods, so that the skins might assimilate the tanning material thoroughly. *Electric tanning* consists in using the electric current to accelerate the process by enabling the skins to assimilate the tanning matter more quickly, thus reducing the time to a few days.

Applied to the *rectification of alcohol*, the electric current is used to remove the bad taste and smell of the unrectified alcohols by hydrogenating the aldehydes, or incomplete alcohols, to which these properties are supposed to be due. For this purpose the crude alcohol is placed in contact with a zinc copper pile, and afterwards passed to special voltameters, in which a strong current carries the action further.

The problem of the *purification of sewage* is one of the pressing problems of the day. It is well-known that oxidation is most effective, and therefore many experiments have been made to utilise the oxidising action at the anode of a voltameter. These experiments have met with a certain amount of success, and are still being continued.

There are other minor applications of the current, but the examples cited will be sufficient to show our readers that in the industrial arts, wherever an oxidising or reducing action is required, or wherever metals have to be deposited in thin layers, the chemical action of the current offers a ready and subtle means for accomplishing the most delicate operations.

CHAPTER XII.

APPLICATIONS OF THE THERMAL EFFECT.

The applications of the thermal effect of the electric current, though much more recently developed than those of the other two, bulk far more largely in the popular imagination. They have attracted much more attention, notwithstanding the fact that as yet they are not nearly so important, either socially or financially, as electric telegraphy, which is an application of the magnetic effect. This attention is, doubtless, due to the greater splendour of the results, and the readiness with which they lend themselves to impressive and gorgeous displays at exhibitions, and in the public streets and places of resort. Also, the enormous quantities of energy dealt with, the massiveness and power of the machinery employed, and last but not least, the general feeling that there may be still more startling developments yet to follow, all tend to impress the imagination in a manner not easily resisted, even where the inclination to resist exists. In most cases the tendency is the other way, and the reins are given to the imagination, with the result that nothing appears to be so wild or improbable but that it may be accomplished by the same agency that has produced the wonders already wrought. These pages will not have been written in vain, if a perusal of them should tend to moderate some of these dreams, by familiarising the reader with the limits imposed by the great fundamental laws of nature, the certainty of which is now so firmly established that there can never again arise doubts of their validity.

The cause of the tardiness above referred to in the utilisation of the thermal effect is not far to seek. To produce any useful amount of heat requires the expenditure of a considerable amount of energy, an amount quite beyond the power of batteries to supply economically. It was, therefore, not until the development of the dynamo machine had made it possible to convert the energy of ordinary fuel into the energy of electric currents that it became possible to utilise the thermal effect of those currents on a large scale.

Electric Lighting.

By far the most extensive applications of the heating effect of the current during the last fifteen years have been in the direction of producing artificial illumination. For this purpose two entirely distinct electrical methods are available. There is, first, the direct heating effect which the current produces in all conductors which it traverses. The laws governing this production of heat have been explained at page 311, and a little consideration will show that, if only the current supplied and the resistance of the conductor be sufficiently great, the production of heat may be so rapid that the conductor will be raised to a red- or white-hot temperature before the loss by cooling balances the heat produced. When this occurs the conductor of course emits light, and with proper appliances the light may be utilised for illuminating purposes.

The second method available for artificial illumination is that which leads to the manifestation of lightning flashes and electric sparks of all kinds. When two conductors at different potentials are brought near to one another with an insulator (or *dielectric*, as Faraday calls it) between them, this dielectric is subjected to a mechanical strain which increases rapidly with an increase of the difference of the potentials of the two bodies. If the potential difference be only increased far enough, the strain on the dielectric becomes so great that it is eventually ruptured, and an electric current passes from the body at higher potential to the one at lower potential through the hole made in the dielectric; at the moment when the disruption occurs a spark or flash of light is seen to pass between the bodies. The fact that there is an actual disruption of the dielectric can be ascertained from an examination of *solid* dielectrics through which the spark has passed; these are always found to be punctured. In the case of *liquids* and *gases* the puncture is, of course, automatically mended almost as soon as produced. Whether the spark is due to the mechanical effects of the disruption, or is a visible appearance of that mysterious entity that we call electricity, is immaterial. For our present purpose it is sufficient to note that in some manner light is produced, and it is only necessary to arrange for a sufficiently rapid succession of sparks for these to be utilised for illumination.

The two kinds of apparatus on which these two different principles are employed for illuminating purposes are known respectively as *Incandescent* or, more briefly, **Glow Lamps**, and **Arc Lamps.** The details of these we shall consider separately.

Glow Lamps.

Historical.—The fact that it might be possible to produce artificial illumination by the raising of an electric conductor to incandescence, was early recognised by electricians. But the first practical attempt was by De Moylens of Cheltenham, who, in 1841, patented a lamp which consisted of a fine wire of platinum in a glass vessel; the incandescence of the wire was to be assisted by a falling stream of particles of plumbago or charcoal.

A much better lamp was invented in 1845 by Starr of Cincinnati, and patented in this country by King. It is most interesting as being the first recorded lamp which made use of the incandescence of carbon in a vacuum. The lamp was contained in an enlargement at the top of an ordinary barometer tube, more than thirty-one inches long and filled in the usual way with mercury, thus producing the well-known Torricellian vacuum at the upper end. For a suitable material for his strip, Starr experimented widely, trying and rejecting many materials, which were again tried and rejected by Edison and other inventors thirty years later. The presence of the long barometer-tube, of course, militated against the practical use of the lamp.

Simultaneously with Starr, De Changy, in France, was also experimenting on carbon and carburated platinum lamps, and met with a certain measure of success. Later on, Starr tried iridium for the conductor, and Nollet, Konn, and others made attempts to use carbon in a vacuum. But the time was not ripe for the successful adoption of an electric lamp using a filament of carbon in a vacuum. Two difficulties blocked the way. The first, to which we have already referred, was the impossibility of producing economically electric currents of sufficient power by means of batteries. The second was still more serious; it was the difficulty of producing a sufficiently high vacuum in the globe in which the carbon is placed. For it must be remembered that carbon at a red heat unites with oxygen and, as we say, burns away. In a lamp using glowing carbon, therefore, it is necessary to remove all the oxygen of the air by efficient air pumps, otherwise the fine carbon rod or filament would soon be consumed. The difficulty of doing this with sufficient completeness led to extensive experiments on platinum, iridium, and other metals as substitutes for carbon, but all metals were found to disintegrate slowly at the high temperatures employed, and their use had to be abandoned. At length, however, the labours of Geisler, Sprengel, Gimingham, and others, and espedially of Crookes, in his "radiant matter" experiments, resulted in the evolution of air pumps so perfect that they only leave in the receivers about one part in every 100 millions of the gases originally contained therein.

Simultaneously, or rather a little later, the Dynamo Machine was considerably improved, and then the time was ripe for the development of the glow lamp.

Modern Glow Lamps.—The first successful glow lamps, of the form which is now so familiar to everyone, were produced by the independent labours of Swan, Edison, Lane-Fox, and Maxim, during the years 1878 to 1880. We do not propose to enter into a controversy as to who was the actual first inventor of a successful carbon filament glow lamp. For our purpose it is sufficient to note that each of the above-named inventors, about the same time, and working independently, produced a practicable and serviceable lamp. Who was first in point of time is immaterial to us, but we may remark in passing that judicial decisions on the priority of the patents involved do not settle the real question, but only the legal one.

Leaving aside these questions, we propose first to describe the glow lamp as it now is, together with some of the accessories which either artistic or practical considerations have associated with its use. Afterwards we shall briefly refer to some of the interesting details connected with it.

Edison and Swan Lamps.—The manufacture of glow lamps in the United Kingdom has been, until quite recently, a close monopoly in the hands of the Edison and Swan United Electric Light Company, which was originally formed by the amalgamation of separate companies engaged in the manufacture of Edison's lamps and Swan's lamps respectively. The latter companies were at one time engaged in litigation with regard to the priority of their respective patents for the construction of glow lamps, and as it was impossible to foresee the result of this litigation, it was decided to amalgamate and thus save some prospective heavy law expenses. The patents held by the amalgamated companies proved sufficiently strong to beat all other competitors in the law courts and establish the monopoly referred to. This monopoly, however, has now come to an end.

The Edison and Swan standard form of 8- and 16-candle lamp is shown in Fig. 237. It consists of a glass enclosing globe through which pass the platinum wires, *p p*, whose ends are bent over and again sealed into the glass so as to form terminal loops to which the current-carrying conductors can be attached. We may remark in passing that platinum is, so far as we at present know, the only conductor which can be passed through glass so as to make an air-tight joint. This is because it is the only known conductor whose co-efficient of expansion by heat is nearly the same as that of glass. In order to pass the metal through, the glass has to be softened by heating it, and at that temperature any metal could, of course, be passed through, and the contact of glass and metal made air-tight. But, on cooling down to the ordinary temperature, if the two do not contract equally, either the glass will be cracked or the metal be loose in the hole. Thus it is necessary that the metal used should have the same co-efficient of thermal expansion as glass, and we have a most interesting illustration of the inexorable rigorousness of Nature's laws.

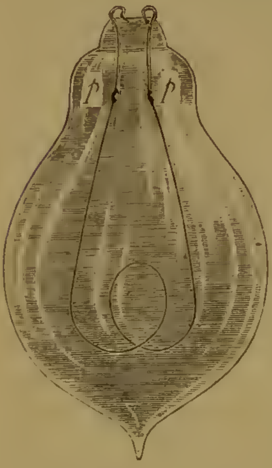


Fig. 237.–Edison and Swan Standard Glow Lamp.

Internally, the platinum wires end in two little spirals or cups, into which the ends of a carefully-prepared carbon filament are inserted, and a good electrical joint made with tar-putty or in other ways. The filament used is very slender, and offers a high resistance to the passage of the current; for instance, the hot resistance of the filament of a 16-candle power 100-volt lamp is about 155 ohms. When, therefore, a current of sufficient magnitude, about 0·64 ampère in the case cited, is passed through the filament, it is raised to incandescence by the heat generated, and emits a perfectly steady and soft light.

One form of holder used with this lamp is shown in Fig. 238 on a somewhat larger scale. The body of the holder is of ebonite or hard wood, and can be screwed into any convenient socket. The two binding screws are metallically connected to the two little spiral springs projecting downwards and terminating in hooks, which are to be inserted in the platinum loops of the lamp. The two large loops of hard brass attached to the holder grip the glass globe tightly and hold it firmly in its place.

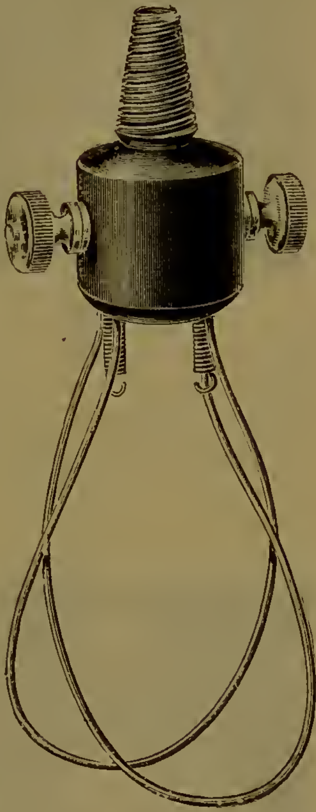


Fig. 238.—Glow Lamp Holder.

The platinum loops represented in Fig. 237, though otherwise a good form of terminal, are somewhat fragile and easily broken off short, in which case the lamp becomes useless. Other kinds of terminals have, therefore, been devised, though in all cases it must be remembered that platinum is used to pass the current through the glass. Some of these terminals are illustrated in Figs. 239 to 241. Fig. 239 shows two forms of "bottom loop cap" terminals, as they are called. An earthenware cap is cemented on to the terminal end of the lamp with plaster-of-Paris, and carries two strong loops which are firmly attached to the platinum loops underneath. In this way the terminals are protected against the evil effects of vibrations, such as exist on board steamers and in other places, as well as against sudden jars.

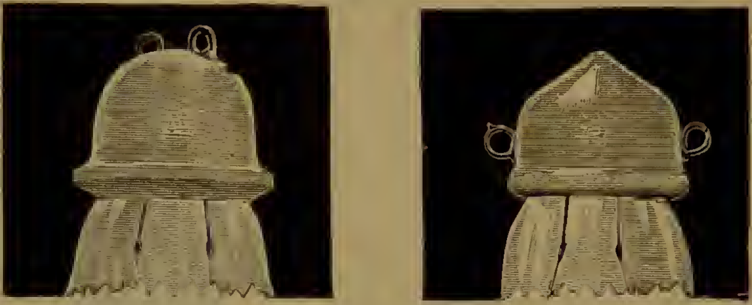


Fig. 239.—Bottom Loop Cap Terminals for Glow Lamps.

Fig. 240 represents the cap originally invented by Edison. The platinum wires are attached, one to a plate of thin brass at the end of the cap, and the other to a coarse screw of sheet brass surrounding it; the inner space and the space between the two pieces of brass is filled with plaster-of-Paris. The cap is used with a special socket, which may be described as its reversed counterpart. The screw on the cap works into a corresponding screw in the socket attached to one of the supply wires, and when screwed home the plate at the end of the cap presses against a plate in the socket attached to the other supply wire. In screwing these lamps home there is a danger of wrenching off the glass at the neck, thus destroying the lamp.

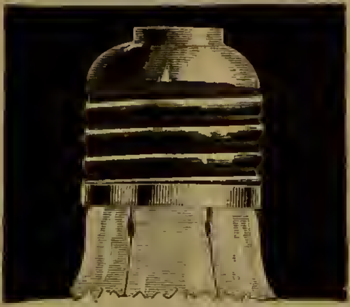


Fig. 240.—Edison's Cap Terminal.

The best form of terminal is, perhaps, that shown in

Fig. 241, and known as the "Brass Collar" terminal. The neck of the lamp is surrounded by a brass collar, secured and filled with plaster-of-Paris. An end view of the collar is shown at the side. The platinum leading-in wires are attached to two plates, *a* and *b*, of stout brass, insulated from one another, and the collar, by the plaster. There are two little studs on the collar, which fit into a bayonet joint on the holder. When placed in the holder the plates *a* and *b* make contact with two brass studs pressed forward by springs, and each connected to one of the supply wires.

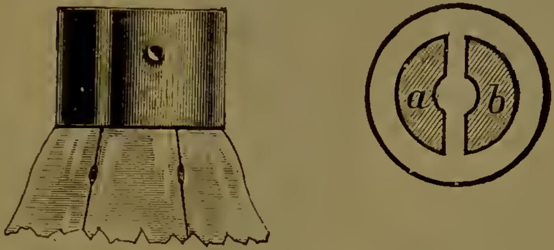


Fig. 241.—Brass Collar Terminal.

Besides the standard lamp of Fig. 237, the Company manufactures lamps for all purposes and of all candle-powers, from one to one thousand. The small candle-power lamps are made in many different forms for various purposes. They may be used for surgical, dental, and microscopic work, for placing in real and artificial flowers, head-dresses, jewellery, miners' lamps, and so forth. As a rule they can be lit up with small and not very heavy secondary or primary batteries. One of these lamps for surgical and microscopic work is shown full size in Fig. 242. A pressure of from four to eight volts is sufficient to make it glow, and when fully incandescent it gives a light equal to that of a single candle.

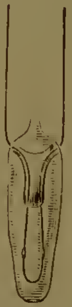


Fig. 242.—Small Microscope or Surgical Lamp.

In glow lamps developing very high candle-powers the Edison and Swan Company places several long high resistance filaments in parallel with one another, so that the current divides amongst them. In this way a much larger radiating or light emitting surface is obtained than would be given if the filaments were replaced by a much thicker one, capable of carrying the total current. For instance, in the 500 candle-power lamp, shown about one quarter of its full size in Fig. 243, there are five such long filaments. One end of each filament is attached to one of two copper rings, which are connected by stout conductors to the leading-in wires. Each of the latter consists of a bundle of fine platinum wires, and the outside terminals are correspondingly massive. The lamp is surrounded by a network of fine wire, to diminish the risk of accidents from falling glass, should the latter

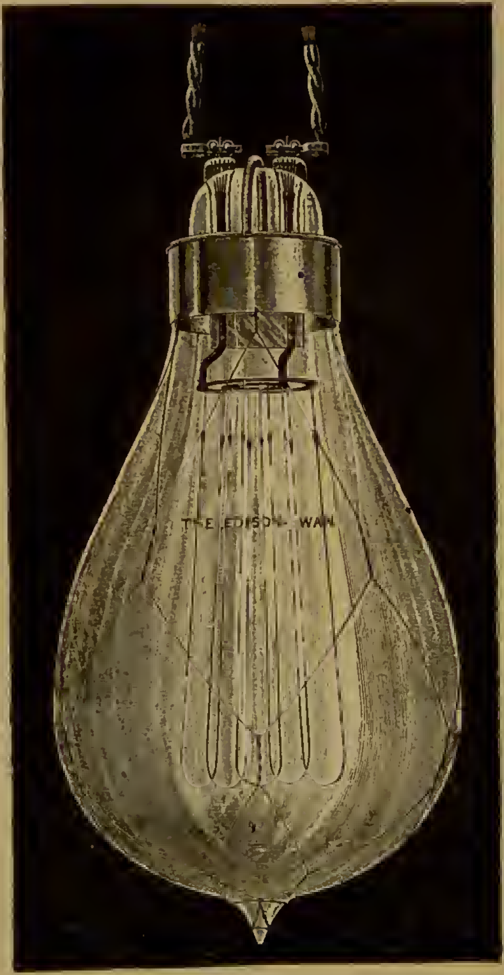


Fig. 243.—500 Candle-Power Glow Lamp.

happen to get broken while in use. The lamp shown takes a current of 18·8 ampères at 100 volts, and, therefore, has an effective resistance of 5·3 ohms, or 26·5 ohms per filament, whilst it absorbs 1,880 watts, or 2·5 horse-power. With this large absorption of energy, as may easily be imagined, the lamp gets very hot.

In conclusion, there is a simple method by which the light of a glow lamp thrown in a particular direction can be much increased. This is accomplished by silvering, as in ordinary mirrors, one half of the bulb. Of course, the light in one direction is quite stopped, but in some positions this is immaterial, and the increase of the light in the other direction is very marked. The same effect can be produced by attaching a suitably-shaped metallic mirror to one side of the lamp, and this method has the advantage that the same mirror can be used for successive lamps.

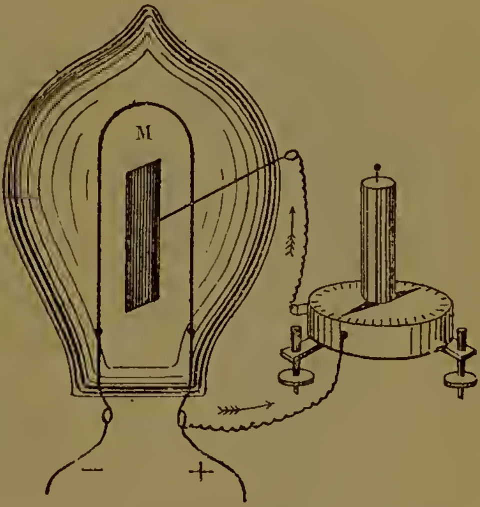


Fig. 244.—Connexions for Showing the Edison Effect.

Physics of the Glow Lamp.—There are several most interesting physical phenomena connected with the glow lamp, which we regret we have not space to describe fully. In the first place, the glow lamp is a more or less perfect vacuum tube, and the various phenomena of electrical discharges in high vacua can be observed in lamps of different degrees of exhaustion.

Then there is a most curious effect known as the

"Edison" effect, first observed by Mr. Edison in 1884, and more recently (1890) examined by Dr. Fleming. A metal plate, M (Fig. 244), supported by a platinum wire, sealed through the bulb, is placed between the two legs of the filament of a glow lamp, so as to form a kind of screen between them; it does not, however, touch either leg, but is well insulated from both. Let now a continuous steady current be sent through the lamp from the right to the left hand terminal, and let the positive or right hand terminal be connected, as shown, through a sensitive galvanometer to the wire supporting the metal plate. The galvanometer will be found to show a steady current of several milliampères,[1] flowing in the direction indicated by the arrows. This, in itself a most curious result, becomes still more curious when we find that on moving the galvanometer wire from the positive to the negative terminal all indications of current cease. How is the phenomenon to be explained? In some way the current in the first experiment must cross the gap between the metal plate and the negative terminal, and Dr. Fleming, by using ingeniously placed screens of glass and mica, has shown that there is a continuous molecular stream of negatively charged particles shot off from the negative side of the filament against the plate.

That particles of carbon are torn off from the filament is evident from the fact that the filament gradually wastes away, usually most quickly at some spot where presumably there is some minute defect. And even in lamps which have not "burnt out," there is after long use a distinct darkening of the bulb, due to deposition of carbon particles. When the filament finally breaks at some point, such as *a* (Fig. 245), very rapid disintegration seems to precede the actual rupture, the bulb becoming darkened very quickly. Moreover, it is curious to note that the disintegrated molecules travel in straight lines, as shown by the opposite leg of the filament casting a well-defined "molecular shadow" on the glass at *b b*, directly behind the unbroken leg, where there is a clear strip on which carbon is not deposited to nearly the same extent as in the immediate neighbourhood.

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[1] One milliampère = $\frac{1}{1000}$th of an ampère.

Light of the Fire-Fly.—A curious investigation was recently undertaken by Professor S. P. Langley for the purpose of comparing the efficiency, as we may call it, of the light emitted by the fire-fly, with that obtained from other natural and artificial sources of illumination. By the efficiency, we mean the ratio of the energy of the radiations which produce luminosity, to the total energy radiated by the luminous source. The result is very interesting. It is well known that the radiations which constitute light lie between certain narrow limits of wave length, and that they are usually accompanied by similar radiations outside those limits, which are unable to excite our sense of vision. In most cases by far the greatest part of the energy of the waves consists of this non-luminous energy. Professor Langley, however, finds that in the case of the fire-fly, practically the whole of the radiations lie within the limits of the visible spectrum. From his numerous results we select the two curves given in Figs. 246 and 247. In these curves the horizontal distances represent wave-lengths in thousandths

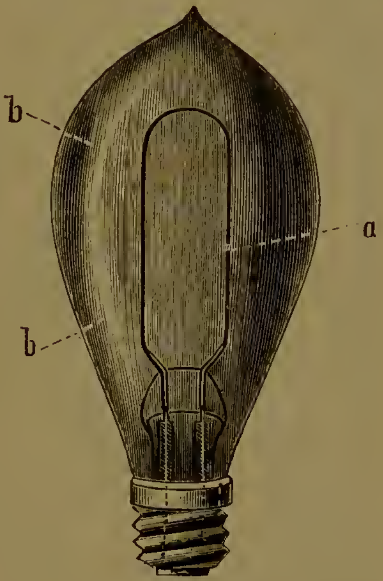

Fig. 245.—Molecular Shadow in Ruptured Glow Lamp.

of millimetres, and the vertical distances represent the energy of the corresponding radiations. The limits of the visible spectrum are shown by dotted vertical lines, and the proportion of the area of the curve between these limits to the total area represents the above efficiency. The curves are drawn to have the same total area. In the first curve, which represents the spectrum of a gas flame, only one four-hundredth part of the total energy lies within the luminous limits. For purposes of illumination the other 399 parts are absolutely useless. But in the case of the fire-fly all the radiations produce light, and the efficiency is 100 per cent. In fact, the curve cannot be completed on the scale of the gas-flame figure, which is the scale adopted, as the vertical distances would exceed the limits of the paper. The height of the curve is 8,700 divisions of the vertical scale. Thus,

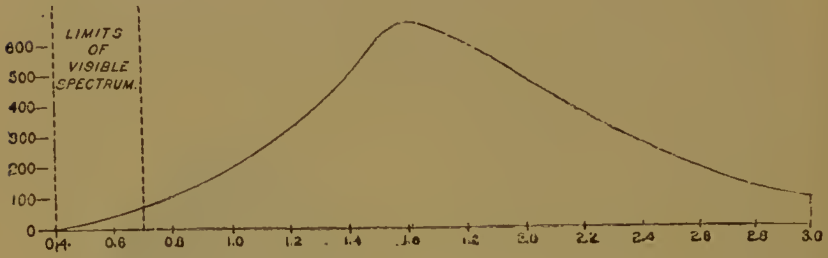

Fig. 246.—Energy Curve of Gas-Flame Radiations.

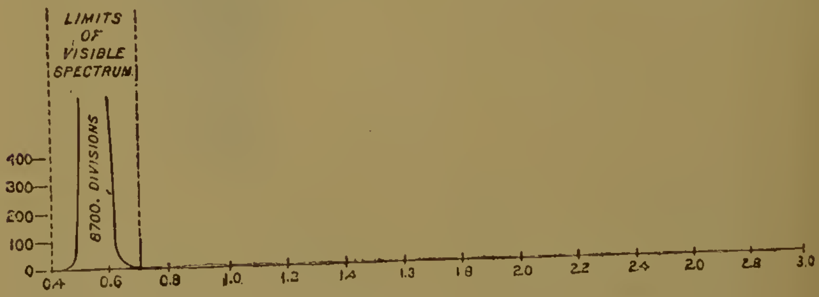

Fig. 247.— Energy Curve of Fire-Fly Radiations.

if we could produce the light of the fire-fly on a large scale, it would be by far the most efficient form of light. Professor Langley considers that such production is not impossible, as vital processes do not seem to be essential to it.

ARC LAMPS.

Historical.—The first to utilise the light from a succession of electric sparks for the purpose of producing an illumination which might be of practical use, was Sir Humphry Davy, who, in 1810, exhibited the "arc" light, as he called it, at the Royal Institution. The origin of the word "arc," now so widely used to designate this kind of light, is curious and interesting. The points between which Davy passed the sparks were in a horizontal line; the air between these points, being heated, ascended, and in doing so caused, between the points, an upward current, which blew the sparks into the form of an "arch." This suggested the name given to the light by Davy; but nowadays, when the separated points are usually in a vertical line, the "arc" form is seldom seen. To produce his arc light on the above occasion, Davy used a battery of 2,000 cells, for he found that without this large number of the primitive cells then available he could not maintain his light. It is, therefore, not surprising that for many years Davy's experiment was only reproduced in the laboratory or lecture room, and it was not until a less cumbrous means of producing the electric current had been provided by the invention of Grove's and Bunsen's cells, that inventors began to turn their attention to improving the details necessary for the production of a steady light.

In 1844 Leon Foucault exhibited a lamp in Paris, in which the position of the carbons was adjusted by hand; but the first to produce an automatic arc lamp was Thomas Wright, of London, in 1845. He was shortly followed by W. E. Staite, who devised several ingenious forms of arc lamps, some of them embodying important details, which have been re-invented during the last few years. In the next ten or twelve years many good lamps were produced by Archereau, Serrin, Foucault, Gaiffe, and others. All these, however, were necessarily supplied with current from primary batteries, and this method of generating electric energy was still too costly for the arc light to come into extensive use. But with the improvement of the dynamo machine the subject again attracted the attention of inventors with better practical success. Before, however, describing a few typical modern forms of arc lamps, it would be well to put before our readers a brief summary of the electrical and other conditions that must be fulfilled in order to procure a steady light. That these may be clearly followed we must first describe the arc itself, as it is now usually formed between carbon points.

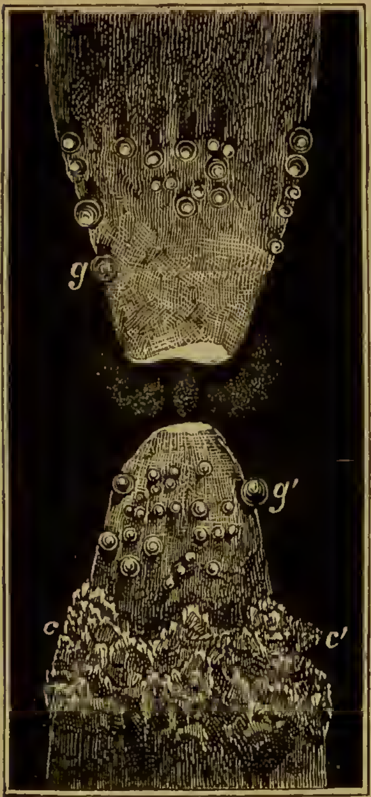

Fig. 248.—Carbon Points of Arc Light.

The Electric Arc. — The appearance presented by the carbon points of an arc light fed by a continuous current is shown in Fig. 248, which is a magnified picture of the carbons after the light has been burning some time. The upper carbon is the positive, and the lower the negative. The extremity of the former is worn away into the shape of a crater, and emits an intense white light; from this crater the greater and certainly the most brilliant portion of the light proceeds. The negative carbon wears away to a point, and is not nearly so luminous as the positive, though it emits a fair quantity of light. The little nodules, *gg*, seen on the cooler parts of the carbons are probably due to metallic impurities. The presence of these impurities causes the light to flicker. Both carbons consume slowly away, but the positive at about double the rate of the negative. The appearance depicted in Fig. 248 is that of the carbons in an ordinary arc lamp using a continuous current at a pressure of about fifty volts. When, however, the arc is formed between two points, subjected to a high alternate potential difference, it presents a very different appearance. In some experiments made by Messrs. Siemens and Halske, an alternate P.D. of about 20,000 volts was used. The resulting arc is shown half-size in Fig. 249. The electrodes were about an inch apart, and the arc formed made a loud "humming and clapping noise, and flapped about, being easily carried away by the slightest draught." In all cases, instead of filling the space between the electrodes, it stood up as shown, thus resembling Davy's original "arch."

The appearance and the behaviour of the ordinary "arc" being as first described, let us consider a little more closely how it is produced.

Primarily we have on the one hand a source of electric current energy, and on the other a piece of apparatus for converting that energy into light and heat. Assuming that the first is so regulated that it will supply the energy at a constant rate under varying conditions, it is the function of the latter to so convert it into light and heat that the intensity of the former does not vary. Now the light and heat evolved are due to the continuous passage of the electric sparks between two points, separated by a dielectric. This passage of the spark is accompanied by the generation of a large amount of heat concentrated in a small space, and consequently the points between which the sparks pass are quickly raised to a high temperature—so high indeed that the most refractory metals are fused. Metallic points, therefore, cannot be used, and yet the material employed must be capable of conducting the electric current to the points. Fortunately, carbon fulfils most but not all the

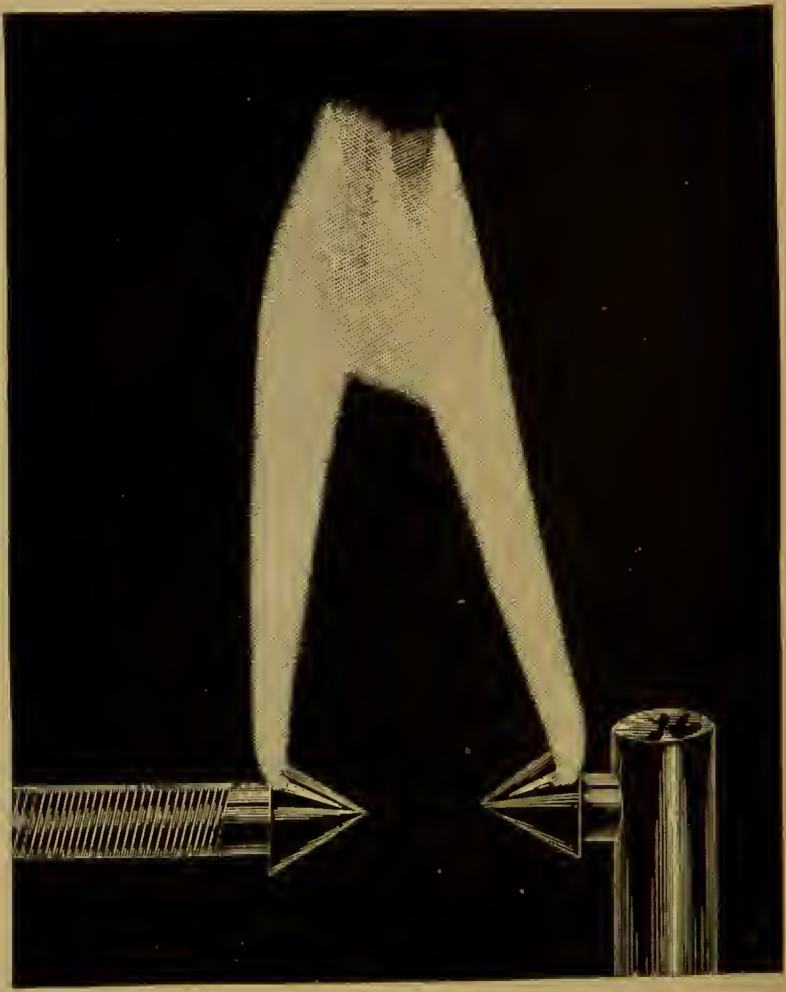

Fig. 249.—Alternate Current 20,000 Volt Arc.

conditions. It is a conductor, and may be brought to an intense white heat without fusion. Its chief drawback is its property of combining with oxygen at moderately high temperatures; but by selecting very hard forms of carbon the rate of combination can be made very slow. Moreover, it is very probable that at the temperature actually attained carbon and oxygen do not combine, or, in the language of the chemist, the temperature is above the dissociation point of carbon monoxide. If this be really the case, the carbon volatilises slowly at the points, combining with oxygen only when it reaches the cooler parts in the neighbourhood of the arc. Whatever the explanation may be, it is certain that suitable carbon points only consume slowly.

Now, any alteration of the distance between the carbon points, or the length of the arc, as it is called, will obviously alter either the potential difference required to produce the same current (or succession of sparks), or the current due to the same potential difference. To keep the light steady it is therefore obvious that arrangements must be made for *feeding* forward one or both carbons at exactly the rate at which they are being consumed. If the rate of consumption were perfectly uniform, this could be done by properly designed clockwork; but practically it is found that whatever may be the motive power used, the *control* of the feeding mechanism must be electrically governed, in ways to be presently explained, by the varying electrical conditions in the arc itself. Another condition is the use of good, pure, and homogeneous carbons; without these no controlling mechanism can be trusted to give a steady light; but as the manufacture of arc-light carbons is now a well-developed industry there is no difficulty in procuring suitable ones.

One other requisite of an arc lamp must be noticed. Experiment shows that with the potential differences usually employed (about fifty volts), however close the carbons are brought together before the current is established, the spark cannot leap across the gap of *cold* air. It is therefore necessary to first establish the current by bringing the carbons into contact; if they are then separated a little, the spark due to the breaking of the circuit leaps across the gap, and is followed by other sparks in rapid succession through the now heated air. Thus the mechanism of an arc lamp must include an arrangement by which the carbons are brought into contact, and then drawn a slight distance apart as soon as the current passes. This is technically known as the "*striking*" mechanism, from the phrase "striking the arc," and should obviously be electro-magnetic, and actuated by the current passing through the carbons.

Thus we see that the constituents of a good arc lamp are good homogeneous carbons, good striking mechanism, and a perfect feed. Other accessories are often added, such as focussing arrangements for search lights, change-over mechanism in double-carbon lamps, and cut-outs, which, if an accident happens to the lamp, automatically remove it from the circuit without interrupting the current.

The fundamental conditions to be fulfilled being so simple have offered an almost boundless field to inventors, who have utilised it to the full; for to produce a workable arc lamp requires little or no originality, and calls for the display of only a moderate amount of mechanical skill. The consequence is that, for many years, the Patent Office has been inundated with arc-lamp patents, many of which have never come into practical use. A lecturer,[1] who has recently had the patience to examine most of these, divides the feeding mechanisms alone into thirteen classes, containing altogether fifty-seven varieties! We do not propose to inflict upon our readers a minute description of even typical examples of these various classes; full details can be found in the paper referred to and elsewhere. For our purpose we shall select two or three lamps interesting either from an historical point of view, or because they have emerged successfully from the struggle for the "survival of the fittest."

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[1] Prof. S. P. Thompson, Society of Arts, 6th March, 1889.

One of the most interesting of historical lamps is the **Foucault-Duboscq**, shown in Fig. 250. Originally designed by Duboscq for use with primary batteries, it was quickly improved by the inventor with the help of Foucault, and for many years either it or the Serrin lamp was used for most laboratory and lecture purposes. Under the special conditions of supply for which it was designed—namely, as a single lamp worked by a battery—it is a remarkably steady and reliable lamp. The carbons, held in suitable clips, designed to admit of adjustment, are mechanically attached to two long racks which are moved up and down by means of toothed wheels. The rack, D, for the lower carbon is directly below it, whilst that for the upper carbon slides in a tube, H, at the side.

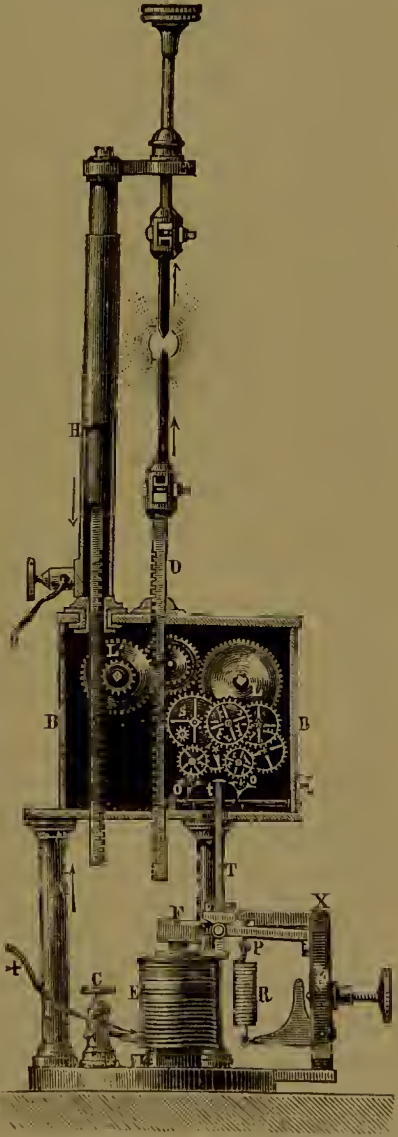


Fig. 250. The Foucault-Duboscq Arc Lamp.

Contrary to the more modern custom, the lower carbon in this lamp is the positive carbon. The toothed wheels, L′, actuating both racks, are on the same axis and move at the same time; the larger wheel drives the positive rack, D, at just double the rate in the opposite direction to that in which the smaller wheel moves the negative rack. As the positive carbon burns away at about double the rate of the negative one, this arrangement ensures that the position of the arc itself shall be approximately the same as the carbons burn away. Within the barrel, L′, is a spring so coiled that it tends to bring the carbons together. There is, however, a third toothed wheel on the axis of L′ which is geared through intermediate wheels to an epicyclic gearing at *s*. This epicyclic gearing is controlled by a double train of wheels, each ending in a star-wheel at O and *o* respectively. These star-wheels are controlled by a detent, *t*, on the end of the lever, T, so placed that when the lever is in the central position the detent, *t*, locks both star-wheels, and no part of the clockwork can move. If, however, the lever, T, moves to the right it releases the star-wheel, O, whilst still holding fast the wheel, *o*. In this case, the left hand train of wheels is free to move, allowing the spring in L′ to feed the carbons forward. On the other hand, if the lever T moves to the left it locks O and releases *o*. In this case the right-hand train of wheels, which is driven by a very powerful spring in the barrel, L, moves and allows the latter spring to draw the carbons apart against the resistance of the weaker spring in L′.

The position of the lever, T, therefore, determines whether the carbons shall be drawn apart, held stationary, or brought nearer together. The lever itself is one arm of a bent lever, whose other arms are F and P. F is the armature of an electro-magnet, E, through which the current passes before reaching the positive carbon. The pull of a powerful spiral spring, R, acts against the attraction of the electro-magnet, and the position of T depends upon which of these forces has the greater effect. When no current is passing through the lamp, R pulls T over to the right, and the spring L′ moves the carbons together till they touch. If now the battery be thrown into circuit a large current passes through E and the short-circuited carbons, causing F to be attracted, T to be moved over to the left, and the spring L to draw the carbons apart, thus striking the arc. The separation of the carbons causes the current to diminish, and for a time the attraction of F is balanced by the pull of R, and T stands in the central position, locking both trains of clockwork. But as the carbons burn away the resistance of the arc increases and the current diminishes; the attraction of F is therefore weakened and T is dragged over to the right, allowing L′ to feed the carbons forward a little bit. As they move nearer together the current again increases, and T is dragged back to the central position, again locking both trains. These actions are continually repeated, and thus the distance of the carbons apart is maintained constant within narrow limits until they are consumed.

With fifty Groves' or Bunsen's cells this lamp gives a steady and reliable light, but such a battery is obviously both troublesome and expensive to work.

In these days, when dynamo currents are usually available, the Foucault-Duboscq and Serrin lamps are chiefly of historical interest, though they can still be used where only a single lamp is required. Another variety of arc lamp, remarkable for its simplicity, is, at the present time, still more completely historical, though more recently developed. This is the so-called **Electric Candle,** invented by Paul Jablochkoff in 1876. The candle consists of two carbon pencils, *a* and *b* (Fig. 251), from one-fourth to one-eighth of an inch in diameter, and separated throughout their length by an insulating and refractory substance, usually consisting of equal parts of plaster of Paris and heavy spar The pencils are fixed in suitable holders, *e* and *g*, which are connected to terminals through which the requisite current is supplied. To start the arc a small piece of graphite or other suitable material, *c*, is laid across the tips of the pencils at the top end, and is held in position by a band of paper or asbestos, *d*. When the current is first turned on this connecting piece soon disappears, and the arc is left playing between the carbon points. The insulating material between the pencils burns away, or, rather, volatilises, at the same rate as the carbons, and thus the candle is gradually consumed. Because of the difference in the rate of burning of the positive and negative carbons in the ordinary arc, the Jablochkoff candle has to be supplied with alternate currents, so that each pencil, being alternately positive and negative, shall burn away at the same rate. All attempts to devise candles to be fed with continuous currents have failed.

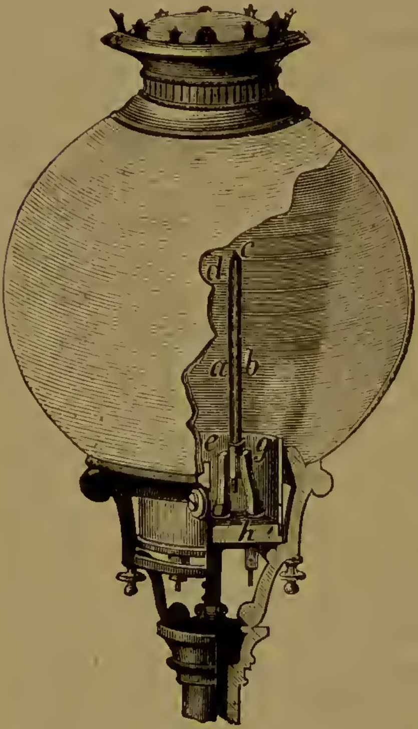


Fig. 251.—The Jablochkoff Candle.

Wilde, Jamin, and others have also designed arc lamps on the *electric candle* principle, but hitherto these have not proved either as economical or as steady as a well-regulated modern arc lamp. We therefore pass at once to the description of a typical form of the latter.

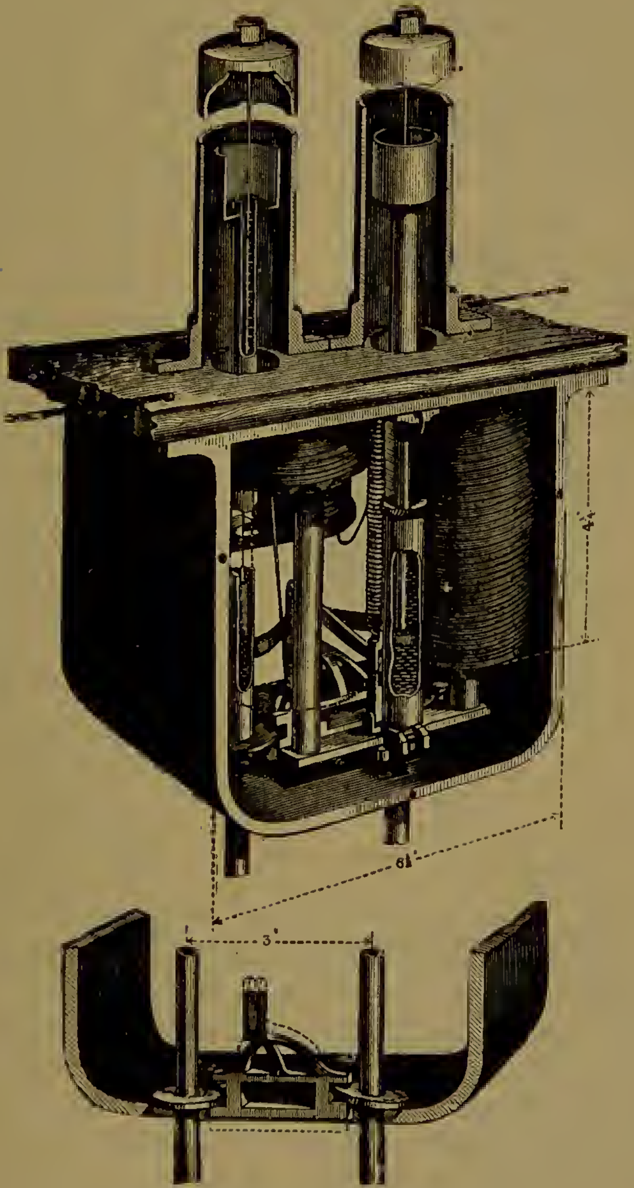


FIG. 252.—MECHANISM OF BRUSH LAMP.

One of the most widely used arc lamps is that manufactured by the Brush Electrical Engineering Company. Originally designed by Mr. C. F. Brush, of Cleveland, it has been from time to time improved in small details, and is now a remarkably steady lamp. The working parts of the most recent form, as used in England, are shown in Figs. 252 to 254. Fig. 252 is a perspective view, with the front cover and one of the large solenoids removed, the better to show the mechanism, other details of which can be seen in Fig. 253, which shows the lamp as seen from the back, and Fig. 254, which is a side section through one of the carbon rods. As in the majority of modern arc lamps, the driving force which tends to bring the carbons together, is the weight of the upper carbon and its holder. Thus, when no current is passing through the lamp the carbons run together and rest against one another. On the current passing, either one or both carbons are drawn apart by the action of an electro-magnet, and then as the carbons burn away they are automatically allowed to approach slowly, under the action of some form of electro-magnetic control.

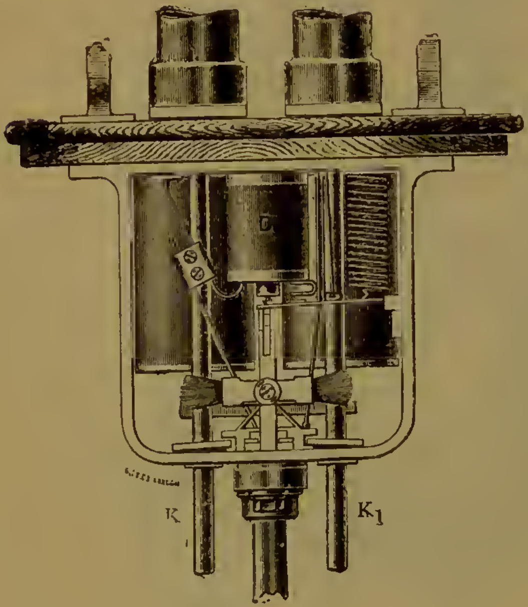


Fig. 253.—Brush Lamp from Back.

The various lamps differ from one another chiefly in the way in which the movements of the armatures of the electro-magnets are transmitted to and affect the carbon holders. The Brush lamp is what is known as a "clutch" lamp—that is, the electro-magnets act on the carbon rods through the medium of a clutch. This clutch is shown separately in the lower part of Fig. 252. It is remarkably simple and consists merely of a flat ring, or washer, as it is called, which surrounds the brass rod which carries the carbon, and when lying flat on the base plate of the lamp allows the rod to slip through quite easily. The lamp we are describing is a "double carbon" lamp, and therefore, in Fig. 252, two rods are shown, each surrounded by a washer. These washers can be tilted by the rectangular-shaped piece of brass which lies between them, and which has projections which pass a little way under the washers. On being tilted, the washers grip the rods firmly, and when further raised bodily lift them up. It will be noticed that the projection on the right-hand side is thicker than that on the left, and therefore the right-hand washer is tilted first, when the rectangle is raised by the electro-magnet. The effect of this is to separate the carbons on the right-hand

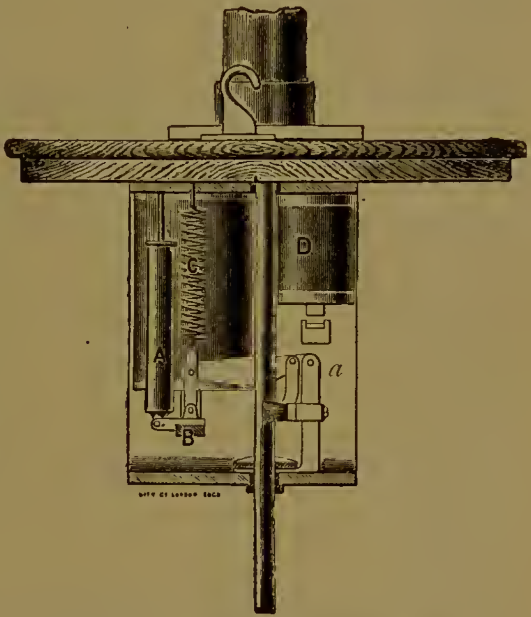


Fig. 254.—Side Section of Brush Lamp.

side first, in which case no arc is struck on that side, as the circuit is not broken, being still completed through the other carbons. Immediately afterwards the carbons on the left are separated and the arc is struck.

The rectangular cross-piece is connected by levers, which can be traced in the figures, with the armature B (Fig. 254) of the large electro-magnets at the front of the lamp; B is attached crosswise to the movable cores of the solenoids, and the weight of these cores and the armature is chiefly borne by the spring C. The solenoids are wound with two circuits, one of thick wire, which is placed in series with the carbons, and the other of fine wire, placed as a shunt across the carbons. The currents circulate in opposite directions in these two circuits, so that their magnetic effects tend to neutralise each other. The particular kind of electro-magnet used has been already described (page 167).

When the current is first turned on, the carbons are touching one another, and there can be very little P.D. between them. Thus, a full current flows through the thick wire circuit and practically none through the thin. The effect of this is to draw up the armature and strike the arc between one pair of carbons in the manner already explained.

But as soon as the arc is struck there is a considerable P.D. set up between the carbons, and an appreciable current flows through the thin wire circuit, weakening the pull on the armature and lowering it. As the arc lengthens, the current in the thin wire circuit gets greater and greater, until the armature is so far lowered that the washer allows the rod to slip through a little and bring the carbons nearer together. As soon as this happens the current diminishes in the shunt circuit, the armature is lifted, and the washer again grips the rod firmly. These movements alternate, and the carbon, as it burns away, is fed forward in a series of almost imperceptible jerks. To steady the action "dash-pots," which can be seen at A in Fig. 254, are fixed both to the upper ends of the carbon rods and also to the armature, B. These "dash-pots" consist of cylinders filled with oil, glycerine, or water, and having pistons attached to fixed rods fitting loosely in them. The friction of the liquid as it passes the piston thus tends to retard any sudden movement of the cylinder.

When the carbons on the left have nearly burnt out, the further "feed" is arrested by a stop, and the arc then soon goes out. As soon as this happens, the carbons on the right, which have been held apart all the while, run together, and then the arc is struck on that side and continues to burn until they also are consumed. In this way the lamp will burn about sixteen hours without the carbons being renewed.

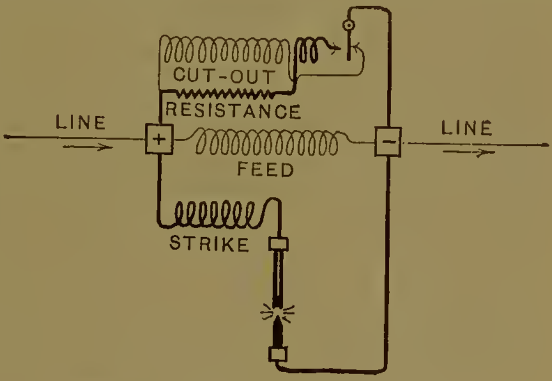


Fig. 255.—Circuits of a "Series" Arc Lamp.

Instead of describing the particular circuits of the Brush lamp we shall give a general diagram, applicable to all arc lamps, which are to be run in "series" with other lamps, in a circuit in which the current is always the same, however many lamps are burning. The necessary connections of the circuits for such lamps are shown in Fig. 255, which is due to Dr. S. P. Thompson. The current, entering at the terminal marked +, divides into two parts; one part passes through the fine wire coil of an electro-magnet marked "feed," and the other through a thick wire coil of an electro-magnet marked "strike," and then through the arc. Both currents re-unite at the negative terminal (—). The two coils may either be wound "differentially" on the same electro-magnet as in the Brush lamp just described, or they may actuate entirely distinct magnets, one of which is reserved for "striking," and the other for "feeding" purposes.

The other circuits shown in the upper part of the figure belong to the "automatic cut-out," the object of which is to provide a path for the current past the lamp, in the event of anything happening to the working parts which would otherwise stop the current. It consists of a fine wire high-resistance electro-magnet, always in circuit, with the current at one point passing through a movable armature, *a*. If the main current through the carbons be interrupted, the current in this fine wire circuit at once rises sufficiently to attract the armature, *a*, against the left-hand contact, which puts a resistance and the thick wire coil of the same electro-magnet into circuit. This coil holds the contact hard over, and the main current now passes through it to the other lamps of the circuit without interruption. In the Brush lamp the two cut-out coils are wound on the magnet D (Fig. 254), below which can be seen the contacts of the movable tongue or armature.

The mechanical devices employed in different lamps to obtain a steady feed exactly equal to the rate of consumption of the carbons are very numerous. In many lamps some form of clutch arrangement is used, the details, however, differing widely from the clutch used in the Brush lamp. In particular, a magnetic clutch is used in the Gulcher lamp, which is largely used for running in parallel with glow lamps. Then another large class of excellent lamps, including the Brockie-Pell and the Crompton, uses some form of brake-wheel control. In these the carbons can only descend when a wheel is allowed to turn, and the electro-magnetic control acts upon a skid or brake applied to the circumference of this wheel. Good lamps of this class are remarkably steady. Then, again, in a much less numerous class, the carbons are moved by the armature of an electric motor, whose working is controlled by the resistance of the arc. Many other devices are used which we cannot even enumerate, but probably the one example we have described in detail will enable our readers to understand the general principles involved in the design of a good modern arc lamp.

At one time great results were expected from a class of lamps which were partly arc lamps and partly incandescent. In these the electric arc was made to play across the face of a piece of marble or other refractory material, which it raised to brilliant incandescence. The light emitted is, on the whole, much softer and mellower than that due to the arc alone. But the results so far have not fulfilled the hopes raised. The light is not easily kept steady, and, as compared with good arc lamps, these "semi-incandescent" lamps are not so economical, as they require a greater expenditure of energy to give the same intensity of light.

Street Lighting.—The use of arc lamps is, without doubt, the most effective method of artificially illuminating streets, railway stations, and large spaces, either indoors or out in the open. The arrangement of the electrical circuits is very simple. Although the arc lamps can be run in parallel with glow lamps off constant potential mains, it is more satisfactory, where a number are being used, to place them in simple series and supply them with current from a dynamo automatically controlled to give a constant current of, say, ten ampères within certain wide limits of pressure. Where alternate high-pressure currents are employed, a small transformer, fixed to the lamp-post or placed above the mechanism of the lamp, will supply the proper current. In the lighting of the City of London, these transformers are fixed in the base of the lamp-post, where their presence cannot be noticed.

Physics of the Electric Arc.—An examination of the phenomena displayed in the electric arc reveals several most interesting and beautiful problems, to which we can but briefly allude.

In the first place, unless the electric pressure between the carbons be kept at 25 volts or more, the arc cannot be maintained. Even with this P.D. the arc hisses very loudly, and cannot be brought to silence unless the P.D. is raised to about 35 volts. To investigate the cause of this, careful measurements have been made of the ratio of the P.D. to the current for different lengths of arc. This ratio would, by Ohm's law, be the resistance of the arc, if the latter behaved electrically, as an ordinary conductor. On an examination of the results, however, it is found that the so-called resistance can be divided into two parts, one of which depends on the length of the arc, whilst the other is constant. The existence of this last term can only be explained by supposing that there is a back E.M.F. in the arc similar to the back E.M.F. we meet with in a voltameter. This supposition has been confirmed by other experiments. The chief difficulty in accepting it is the high voltage involved; for the "silent arc" this is as much as 33 to 35 volts, and in no other direction do we find chemical or physical changes capable of giving more than 3 or 4 volts.

As bearing on this question, it is a matter of common knowledge that with continuous currents the positive carbon is much brighter than the negative. More exact observations have shown that the intrinsic brightness of the positive carbon is always the same, so much so that it has been proposed to use it as a standard of light. Now, the fact that the brightness is always the same points to a constant temperature, and attempts have been made to estimate this temperature. But if the temperature be constant, its constancy must be due to some physical change taking place. Thus, we know that the temperature of melting ice is constant at 0° C., and that the temperature of water boiling under ordinary pressure is constant at 100° C. By analogy we are led to infer that the change taking place at the positive crater is the *volatilisation of carbon*, and that the back E.M.F. set up is due to the *latent heat of vapourisation* of carbon.

The reason for the lower back E.M.F. of the hissing arc is not quite so obvious. It is always a very short arc, and the negative carbon is brighter than in a long arc. It seems probable that there is a condensation of carbon vapour, drawn from the positive carbon, on the negative carbon. In this condensation some of the energy absorbed in vapourisation at the positive carbon would be restored to the circuit, and the net energy absorbed in vapourisation diminished, leading to a lowering of the back E.M.F.

The high temperature of the carbons also accounts for the small amount of combination of the carbon with the oxygen of the surrounding air. It is a well-known chemical fact that, at high temperatures, compounds become dissociated into their elements, or, in other words, many chemical combinations cannot take place at all at high temperatures. If, therefore, as seems certain, the temperature of the arc is above the dissociation temperature of carbon monoxide, no combination of carbon with oxygen can take place in the arc itself. Combination can only take place as the slowly volatilised carbon vapour reaches the cooler regions in the vicinity.

Not only is a minimum P.D. required to actuate an arc lamp, but it is also found impossible to make an arc lamp burn with less than a certain current. Two or three ampères seem to be absolutely necessary. It appears to be impossible so to adjust the excess of the P.D. of the carbons over the back E.M.F. of the arc that the ratio of this excess to the real resistance will give a small current. The heating effect of the large current on the actual resistance is probably the cause of the difficulty.

We cannot conclude this part of our subject without describing an experiment by Dr. Fleming, in which he shows that the "Edison Effect" (*see* page 496) in glow lamps is represented by an analogous effect in arc lamps. The arrangement of the apparatus is shown in Fig. 256. An idle electrode, in this case a third carbon, is introduced into the arc, and represents the metallic plate in the glow lamp experiment. The introduction of this idle electrode can be more easily effected if the arc be repelled to one side by the action of a magnet, as shown in the figure. The third carbon is connected to a galvanometer, and on joining the other terminal of the galvanometer to the negative carbon, no current can be detected. But on joining the second terminal of the galvanometer to the positive carbon a strong current is observed, and this current can be made to ring an electric bell, or light a small glow lamp. As in the glow lamp, so in the arc, there seems to be a stream of negatively charged molecules from the negative electrode. There are, undoubtedly, some interesting unsolved problems connected with both these methods of artificial illumination.

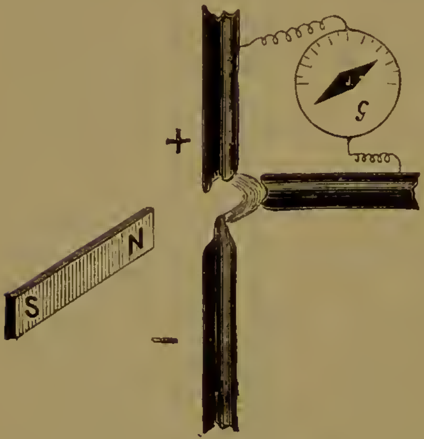


Fig. 256.—Dr. Fleming's Experiment with the Electric Arc.

PHOTOMETRY.

We have now described the appliances used for producing artificial illumination by means of the electric current. But, connected with the subject, and perhaps of even greater interest to some of our readers, is the question of the actual amount of light obtained, and how it is to be scientifically measured. This is all the more necessary, as even amongst those who should know better, wild statements are oftentimes made. Thus arc lamps have been sold as 2,000 candle-power lamps, which, when burning under the best conditions, do not emit a light equal to that of 1,000 candles. Nor are the "electric light men" the only offenders in this respect; gas producers are even worse, for the phrase "20 candle-power gas" has little meaning for the ordinary consumer, who, with the appliances he uses, seldom gets out of it a light equal to that of 5 or 6 candles per burner. A slight digression on the subject of Photometry, or "Measurement of Light," may therefore be more than interesting.

In order to estimate the value of any artificial illuminant it is obviously of primary importance that we should be able to measure the amount of light emitted in terms of some unit. The problem is a twofold one: we have first to select a standard with which we can compare the light or the illumination, and then we have to devise suitable means for making the comparison.

Of these the most difficult is the selection of a satisfactory standard source of light, which can not only be easily produced, but can be relied upon at all times to emit a definite amount of light. The standard adopted by Act of Parliament in this country is the sperm candle, so made as to burn 120 grains of spermaceti per hour. This standard is by no means constant: different candles, all constructed so as to satisfy the requirements of the Act, may vary as much as 15 per cent in the light emitted. In France the Carcel burner, a form of oil lamp, is used; for standard purposes the wick must be of 1·2 inches diameter, and consume 1·48 ounces of purified rape oil per hour; the flame also must be adjusted to a height of 1·6 inches. The light given is equal to that of about 9·6 standard candles.

In 1881 a Parliamentary Committee reported on the

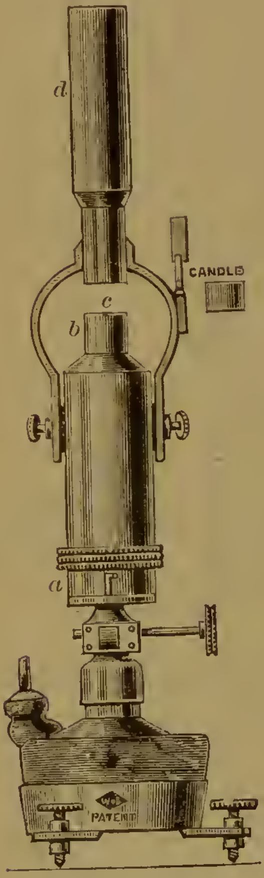


Fig. 257.—Harcourt's Pentane Standard.

defects of the standard candle, and favourably mentioned the "pentane" standard, devised by A. Vernon Harcourt. The apparatus for producing this standard is shown in Fig. 257, and is the outcome of a long series of experiments. The fuel burnt is pure pentane, which is a paraffin having the formula C_5-H_{12}, and boiling at 38° C. This is contained in the lower part of the lamp, which resembles an ordinary paraffin lamp, except that it is provided with levelling screws. The oil passes up through a wick, which ends at the lower part, *a*, of a metal tube, open top and bottom. When the lamp is being used this tube is hot, and vapourises the pentane as it reaches the top of the wick. The pentane vapour passes up the tube, and is ignited at the top end, close to *b*. The actual tube is not seen in the figure, as it is enclosed by two other tubes, the outer of which is narrowed at the top end, *b*. This outer tube also carries the upper metal chimney, *d*, whose height can be adjusted by screws and slots on the carrying arms, so that the gap, *c*, can be made of any desired width. It is in this gap that the part of the flame used for photometer work appears. Two adjustments are necessary. First the total height of the flame must be such that its top can be seen between two slots, about half an inch high, in the upper chimney And, secondly, the gap, *c*, must be a certain width. To fix the latter gauges are supplied, the gauge for a light of one candle-power being shown at the side, marked "candle. To start the lamp the outer jackets of the lower tube have to be removed, and this lower tube warmed, so that it can vapourise the pentane.

Many experiments with this lamp have shown that, when a few necessary and simple precautions are observed, the light emitted can be relied upon with a probable error of less than one per cent.

Other standards have been proposed to replace the unsatisfactory "candle." For instance, the Congress of Electricians, at Paris, in 1881, decided that the standard of light should be the light emitted by a square centimetre of platinum, just before it fuses. This standard, however, is obviously difficult to procure, though M. Violle has designed an apparatus for producing it, the platinum foil used being heated by an electric current. The light emitted is rather less than that of two average standard candles.

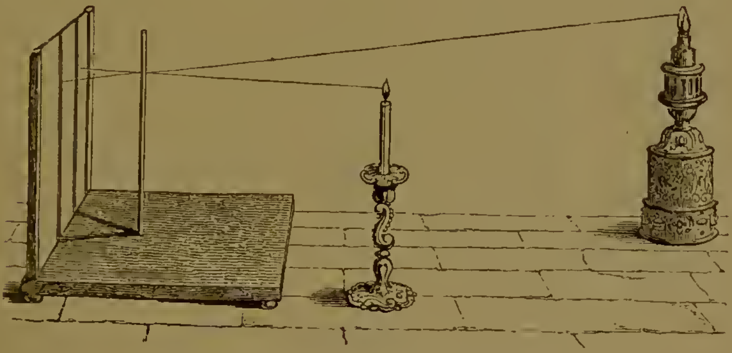


Fig. 258.—Principle of Rumford's Photometer.

The second branch of photometry consists in the comparison of the light under examination with the standard light. The general plan is to so place the two lights to be compared that they produce equal illumination on a given screen. The methods of determining when the illuminations due to the two lights become equal are very various, and some of them are complicated. One of the simplest is that somewhat diagrammatically depicted in Fig. 258, which represents a form of photometer devised by Rumford. A blackened cylindrical stick is set up in front of a screen with a dead white surface—for example, a surface of white blotting paper. The lights to be compared are placed on the side of the stick remote from the screen, in such positions that they throw on the screen two shadows alongside one another. In practice the shadows are arranged so as not to overlap, but just touch. Now it is evident that one of these shadows is illuminated by one light only, and the other by the other light. As they are alongside they are in a good position for determining when they are equally bright or dark. One of the lights is moved to and fro, until the observer considers that he has obtained this effect. He then measures the distances of the two lights from the *screen* (the position of the stick does not enter into the calculation), and takes the relative intensities to be proportional to the *squares* of these distances, according to a well-known law in optics.

Two difficulties present themselves in practice. First, if the lights are of very different colour—for instance, an arc lamp and a candle—it is almost impossible to say definitely when the two shadows are equally dark. An attempt is made to get over the difficulty by examining the shadows through coloured glasses, but this only enables the relative intensities to be compared as regards the kind of light transmitted by the particular coloured glass used.

Secondly, if the two lights differ greatly in candle-power, one must be placed at an inconveniently great distance. For instance, in comparing an arc lamp of 1,600 candle-power directly with a standard candle, the arc lamp must be forty times further away from the screen than the candle. As the candle, for several reasons, should not be placed closer than 10 or 12 inches, this means that the arc lamp must be 33 to 40 feet distance. Not only is the actual distance inconvenient, but an error is introduced owing to the absorption of the light from the arc in passing through so great a length of the atmosphere. To shorten this distance many devices have been proposed. The light from the arc may be diminished by rotating screens, or dispersed by a double concave lens, or weakened in a known proportion in other ways.

One good plan is to use an intermediate light as a kind of "step down." This method was employed at the Munich Exhibition. A diagram of the plan adopted is given in Fig. 259. The standard light is placed at A, the arc lamp to be tested at C, and a Siemens' gas burner at B. Movable screens are placed at *a* and *b*. The gas burner was compared with the standard on screen *a*, and the arc lamp was compared with the gas burner on screen *b*. Thus, indirectly, the arc lamp was compared with the standard.

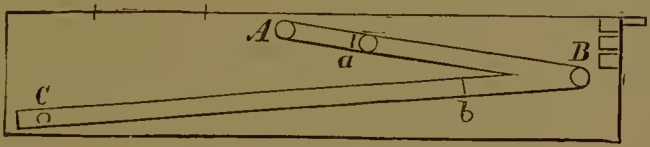


Fig. 259.—Arrangement of Photometers.

In this case the lights to be compared were on opposite sides of the screen, which was translucent, or semi-transparent. The two sides of the screen were assumed to be equally illuminated when a spot of grease on it disappeared. This method of determination, which is very widely used, was devised by Bunsen.

We have, perhaps, now said sufficient to indicate the general methods and problems involved in photometry. The whole subject is somewhat complex, and would require a large amount of space to develop fully; for such developments we must refer the reader to special books.

PRIVATE HOUSE ELECTRIC LIGHTING.

Thus far, in connection with the subject of electric illumination, we have only described the lamps and their immediate accessories. But the possession of these alone, though indispensable, is no more sufficient than the possession of suitable gas burners, brackets, and gasaliers would be sufficient for the purpose of illumination by gas. In both cases we must have the means of distributing the illuminating agent throughout the building to the points where it is to be used, and, in addition, where no public supply of this agent is available, we must incur the expense of erecting the needful plant for its production.

The public supply of illuminating gas, having had about one hundred years for its development, is much more extensive than that of its more modern rival, the electric current. Notwithstanding this, there are still many country districts in the United Kingdom and all civilised countries, where no public supply of gas is available, and where, if the private individual wishes to use this illuminant, he has to incur the somewhat high cost of manufacturing it for himself. When we turn to the electric current, the case, as might reasonably be expected, is much worse, for not only country districts, but even many towns, are still destitute of public supply stations. Fortunately, in these cases, the putting down and the working of private generating plant is a comparatively simple matter, and many hundreds of such plants are now in everyday use. The chief electrical parts, the dynamos and lamps, of a private installation have been already described. How these are combined, and what additional apparatus is necessary or advisable, must now be discussed. Afterwards we shall refer to the fitting of the house or building to receive the current, whether the latter be supplied by the owner's plant or by a public supply company or corporation.

The first requisite in the complete installation of an electric lighting system is some source of mechanical power, or prime mover, for the purposes of driving the dynamos and supplying the energy, which is to be afterwards converted into heat and light. In mills and factories the requisite power can usually be spared from the large engines employed in the general work of the place, but in private houses this source of power is not available. In the latter case it will be necessary to put down special plant for the purpose. The choice will, as a rule, lie between steam, gas, and oil engines, though in mountainous or hilly districts a more satisfactory source than any of these may be found in a turbine worked by a supply of water drawn from some neighbouring stream or waterfall.

Except in special cases, the laying down of a steam boiler and engine is not advisable. The former requires a certain amount of skilled attention and, where only occasionally used, some time and fuel have to be spent in getting up steam, and a good deal of energy is lost in the cooling of the boiler between successive runs. Moreover, even a large steam engine is not so economical a transformer of heat into mechanical energy as a small gas or oil engine. In addition, a gas engine can always be started in a few minutes, and when stopped all further consumption of fuel simultaneously ceases. Moreover, a steam boiler requires a supply of good water. We shall, therefore, pass on to consider briefly the setting up of a gas or oil engine.

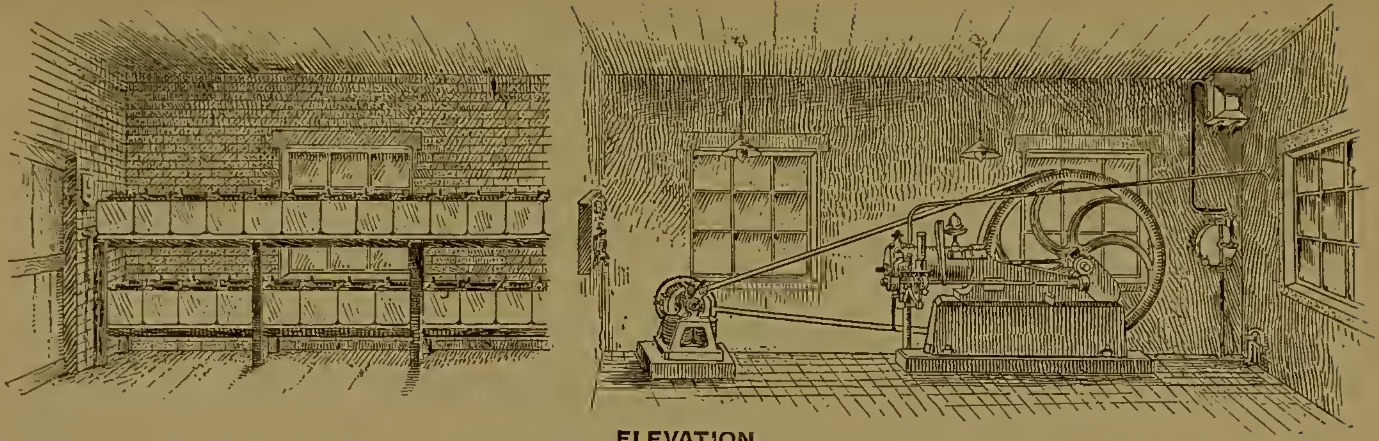
For definiteness, we may take the case of a house wired for 100 glow lamps, each of 16-candle power. This would be sufficient for all purposes in a moderate-sized country house, and though many of the details are not strictly proportional to the number of lamps fixed, it will probably enable our readers to form an approximately correct estimate.

We may premise that in all such cases a secondary battery should be included in the plant; for, although this battery will add considerably to the cost, it is a valuable auxiliary in a self-contained installation. Without it no light, even a single lamp, can be procured except when the engine is running. With it, the engine can be stopped during the small hours of the morning and the whole of the day, and yet a few lamps can always be available in bedrooms, cellars, etc. In fact, if a large battery be laid down, the engine need only be run once or twice a week to charge it; but this course is still more advisable when a steam engine is used, and is not so necessary with a gas or oil engine. Another advantage of using a battery is that it enables the engine to be run at its full, which is usually its most economical, load, whether there be few or many lamps alight.

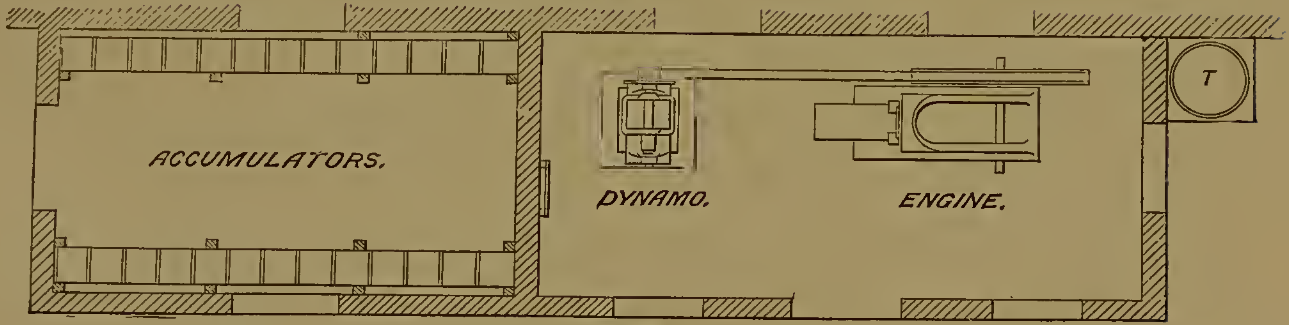
The 100 lamps, if all burning at once, would require about 6,000 watts (6 kilowatts), irrespective of the loss in the leads, but in no ordinary case are all the lights in a house burning at the same time, and therefore a 5-kilowatt dynamo will be more than sufficient. This will require a 4 nominal horse-power gas or oil engine to drive it, for such an engine will give off over 6 horse-power when required.

If 100-volt lamps be used, a battery capable of discharging at the rate of 20 ampères will be quite large enough, and in this case 53 to 55 cells, giving about 2 volts each, will be required. This battery will be able, unaided, to run rather more than 30 lamps. But the installation may be run at a lower voltage, say 60 volts, and then only 33 or 34 cells will be required; but these should be capable of discharging at a rate of 30 ampères, and should therefore be rather larger cells.

The various considerations entering into the question of high or low voltage are dealt with subsequently in the chapter on the "Transmission of Power." We may add



ELEVATION.



PLAN.

FIG. 260.—ARRANGEMENT OF GAS OR OIL ENGINE PLANT.

here, however, that where two or three arc lights are required for the grounds or a long carriage drive, the 60-volt pressure may be found most convenient.

A very neat arrangement of the above plant, devised by Messrs. Drake and Gorham, is shown in Fig. 260. A good, dry, and well-drained one-storey outhouse is most suitable. Two rooms will be required, one for the dynamo and engine, and the other for the battery. The latter has to be placed in a separate room because of the acid spray given off during charging, as this spray would soon damage the exposed metal parts of the engine and dynamo. It is well not to have any door between the two rooms, as even this may carelessly be left open. The engine-room should be well lighted and, for the size of plant considered, should be about 18 feet long by 9 feet wide. The battery room may be small, about 11 feet by 6 feet being sufficient.

The figure is almost self-explanatory. The regulating gas bag and meter are shown on the far wall at the right; these, of course, are not required with an oil-engine. The water-tank, which contains the water for keeping the cylinder cool, is placed outside the window at T. The switchboard is on the left hand wall close to the dynamo, and from it quite short leads pass to the secondary battery in the room behind.

At first sight it might seem to be a mistake to recommend the use of *gas* engines in a country house, where most likely a supply of gas is not procurable. But apart from the many cases in which such a supply is available, it is quite possible to make the gas required for the engine, and that at a cost well below the ordinary charges of gas companies. The gas so made would be useless for illuminating purposes, but is excellent for burning in the gas engine. So much is this the case, that even in towns large gas engines are now replacing steam engines, the gas required being manufactured on the spot. The plant used is very simple; but we cannot for want of space describe it here.

Where a secondary battery is used, the dynamo should be simply *shunt-wound.* The reason for this is the danger of reversing the polarity of a series-wound dynamo. Suppose that, when charging the battery, the speed of the engine drops so far that the E.M.F. generated by the series dynamo is less than the back E.M.F. of the battery. In this case the current will be reversed, and the battery will discharge through the dynamo and will reverse the polarity of its field-magnets. The consequence will be that the E.M.F. of the dynamo will be reversed and assist the battery current, and for a moment an enormous current will flow, calling into play some safety device which will break the circuit. But the mischief does not end here, for when the dynamo is restarted and run up to its proper speed its polarity will be found to be still reversed, and, therefore, on connecting the cells a violent discharge will again take place. These evils are minimised by using a shunt-wound dynamo; for when the current reverses, owing to the slowing down of the engine, it still flows in the same direction through the field magnets, and the cells simply drive the dynamo as a motor. This is not desirable, but no great harm will be done, as the engine, being relieved of its load, will soon speed up again, and the normal state of affairs be re-established.

Passing now to the switchboard, the different switches and instruments thereon may be arranged in various ways, but the simpler the arrangement the better. A very simple form of switchboard designed by Messrs. Drake and Gorham is shown in Fig. 261. It carries two ammeters, one for the dynamo and the other for the lamp circuit, two ordinary switches for the same circuits, and a regulator switch. The latter requires a word or two of explanation.

When a secondary battery is being *charged*, the pressure of the charging current has to overcome not only the ohmic resistance of the battery, but also the back E.M.F. Thus, the P.D. at the terminals must equal the E.M.F. of the battery *plus* the volts (C × R) lost in overcoming the internal resistance. But when the battery is being *discharged*, the *maximum* pressure available is the E.M.F. of the battery, which is approximately the same as during charge. This pressure, however, has to drive the current

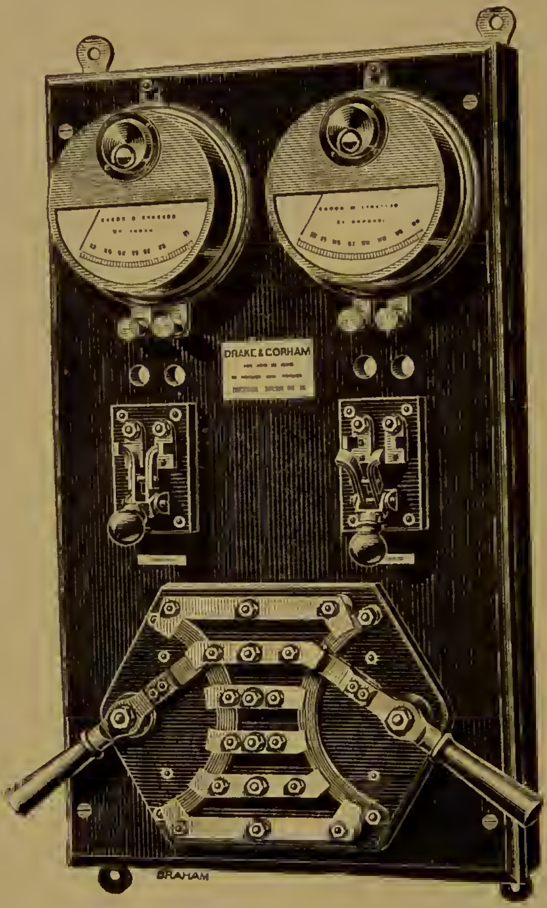


Fig. 261.—Switch Board for Private House Installation.

through the battery, as well as through the external circuit. The P.D. at the terminals will, therefore, now equal the E.M.F. of the battery *minus* the volts (C × R) lost in overcoming the internal resistance. If now, whilst the battery is being charged, some lamps are taking current in parallel with it from the dynamo, the P.D. required by the lamps will determine the number of cells that can be charged in parallel with them. On stopping the dynamo, the lamps will take current from the cells. But the P.D. of the latter will fall for the reasons just given, and the lamps will burn dimly. To bring back the lamps to the requisite incandescence some extra cells must be switched into circuit, so as to increase the available E.M.F. and restore the P.D. to the required value.

The regulator switch at the bottom of the board (Fig. 261) is for the purpose of making these changes rapidly and simply. Conductors are brought to the six cross-bars of the switch from the negative terminals of the last six cells of the battery, which are called regulating cells. These cross-bars overhang, without touching, the circular arcs on the right and left. The arc on the right can be connected, through the switch and ammeter directly above it, to the main negative conductor, which brings the current back from the lamps; whilst the arc on the left can be connected through the other switch and ammeter to the negative terminal of the dynamo. Each arc can be placed in contact with any one of the six cross-bars by means of sliding-spring contacts at the ends of one of the radial arms. By moving these arms, therefore, the number of cells, either in the lamp or dynamo circuit, at any time can be altered.

The two smaller switches enable the dynamo or the lamp circuit to be made and broken at pleasure. Thus, if both switches are "on," the dynamo and the battery are both in circuit with the lamps; when the battery is lighting without the dynamo, the left-hand switch, marked "dynamo," is "off," and the other, marked "lamps," is "on"; whilst when the dynamo is charging only and the lamps are not being used, the left hand one is to be "on," and the right hand one "off."

The left-hand ammeter measures the current given by the dynamo, and the right-hand one the current supplied to the lamps. The *difference* of the readings gives the charge or discharge current of the battery. Thus, if the "dynamo" current be greater than the "lamp" current, the battery is being charged by a current equal to the difference between the two; whereas, if the "lamp" current be the greater, the battery is supplying a current equal to the difference between it and the dynamo current. An inspection of the ammeters will, therefore, always reveal whether the battery is charging or discharging.

The current, whether given off from the battery, or generated by the dynamo, is next conveyed to the house, for which purpose a pair of well-insulated copper conductors are used. The gauge of copper depends upon the maximum current to be carried, and is usually calculated on the supposition that one square inch of section will safely carry 1,000 ampères. As, in the case we are considering, the maximum current may be taken at 50 ampères (for a 100-volt pressure), this would require a cross-section of $\frac{1}{20}$th ($=\frac{50}{1000}$) of a square inch, which would be nearly given by a cable of 19 wires of No. 17 gauge, having a resistance of 0·174 ohm per 500 feet of double cable. The rule is a rough one, and in some cases it would be advisable to lay down a thicker cable so as to diminish the loss in pressure over a long distance. For instance, the above cable would lead to a loss of 8·7 ($=50 \times 0{\cdot}174$) volts at a full load of 50 ampères if the house were 500 feet distant from the dynamo- and battery-room. A change of this magnitude between small and heavy loads would seriously affect the lamps.

Passing now to the house itself, the first operation is to provide conductors to carry the current to the points where light is required. This is technically called "wiring" the house. Theoretically, the arrangement of the conductors is very simple, the lamps being arranged in parallel circuit, as explained at page 288. Perhaps Fig. 262 will assist the reader to understand how the various ramifications depend

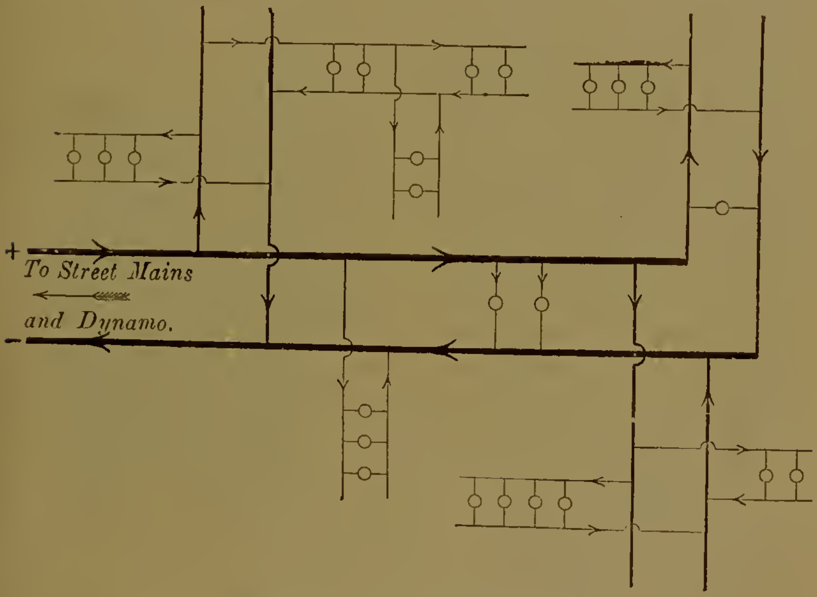


Fig. 262.—Diagram of Glow Lamp Lighting of a House.

upon one another. The figure is strictly diagrammatic, all switches and cut-outs being omitted. The lamps are represented by small circles, and it will be noticed that *each* of these forms a bridge from a conductor directly connected to the + main from the dynamo to a conductor similarly connected to the — main. The arrow-heads show the directions of the currents at various points.

The conductors themselves, technically known as the "leads," should consist of tinned copper wire well insulated with indiarubber, and mechanically protected with other coverings. Elaborate rules have been drawn up for the guidance of contractors in wiring houses, with the object of eliminating all risk from fire due to the heating effect of the current. We shall not trouble our readers with these rules in detail, as they are chiefly such as would be dictated by common sense, combined with a knowledge of the electrical laws to which we have already fully referred. Good, honest workmanship is absolutely essential. The + and — wires are usually run in separate grooves in a dry wooden casing, and are covered over, but should be easily accessible. The sizes of wires should be proportioned to the maximum currents they may have to carry, the rule being to allow $\frac{1}{1000}$th of a square inch per ampère, but it is now usual to employ no wire of smaller gauge than No. 18, though this can carry current for three lamps of 16-candle power at 100 volts. The "insulation resistance" from either conductor to the earth should not be less than 125,000 ohms where 100 lamps are used, and should vary inversely with the number of lamps.

Fusible Cut-outs.—Notwithstanding the greatest care in running and insulating the wires, it is possible that now and again the insulation may break down, and this may lead to a dangerous excess of current in particular wires. This contingency is effectively guarded against by a proper distribution of what are known as "fusible cut-outs." These essentially consist of short lengths of conductors of high resistance per unit length introduced into the current at convenient points. The resistances and sizes of these conductors are such that if the current through them rises 50 per cent. above its normal maximum they melt and so break the circuit. There are many forms of these cut-outs or fuses, but we can only refer in detail to one of the best, which is depicted in Figs. 263 and 264. In Fig. 263 the cover is removed, so as to show the method of fixing the fuse on one of the conductors of a pair of leads running vertically. In this case the base of the fuse-holder is of porcelain; the left-hand lead has been cut and the ends brought through two holes in the porcelain to the screws *a* and *c* respectively. The screw *a* is on a brass block, on which is another screw, *b*, and a fourth screw, *d*, is on the same brass block as *c*. The fuse proper, *d f b*, is hung between the screws *b* and *d*, and therefore the current has to pass through it in order to continue its course along the left-hand lead. This fuse, shown separately in Fig. 264, consists of a lead or tin wire loaded at the centre with a relatively heavy leaden weight. The object of the latter is to ensure that as soon as the metal melts, the circuit shall be interrupted by the breaking of the wire *d f b*. It may appear to be a needless precaution to load the fuse wire with a weight, but it must be remembered that the wire of the fuse, being exposed to the air, may become covered with an infusible oxide. Cases have been known where this oxide has become sufficiently thick to support the molten metal inside, and thus the circuit was not broken although the metal of the fuse had melted.

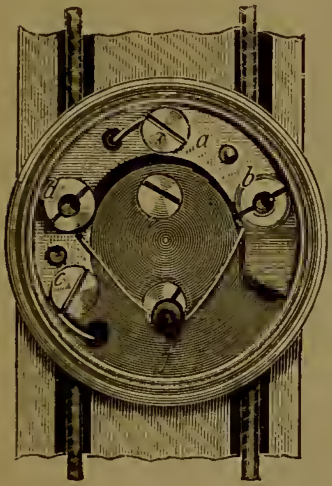


Fig. 263.—Cockburn's Weighted Fuse.

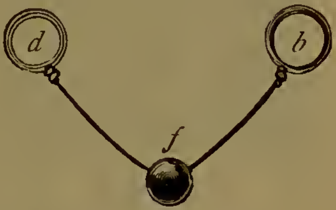


Fig. 264.—Fuse Wire of the "Cockburn" Fuse.

The conditions for a good fuse are that it should "go" as soon as the current reaches a certain value, that the gap it makes in the circuit should be wide enough to prevent the formation of an "arc," that it should be mounted on an incombustible base, and that it should be easily replaceable after fusion.

The proper position for the fusible cut-outs is wherever in the numerous bifurcations indicated in Fig. 262 there is a change of gauge in the conductor used. In an ordinary installation it is usually convenient to have distributing boxes at various points, as a rule on each floor, from each of which a distinct group of circuits branch off. The cut-outs for these circuits can then all be placed in this box, and are readily accessible. Such a box, fitted with "Cockburn" fuses on both sets of leads, is shown in Fig. 265, and will serve to illustrate the principle involved. The positive and negative mains are permanently connected to the two vertical bars marked + and —. From the bar marked + currents can flow through the various fuses to the circuits connected to the screws *a*, *b*, *c*, . . . ; after flowing through the lamps they return to the corresponding screws *a′*, *b′*, *c′* . . . on the other side, and reach the — bar through another set of fuses. In this arrangement there are fuses on both the positive and negative sides of the lamps.

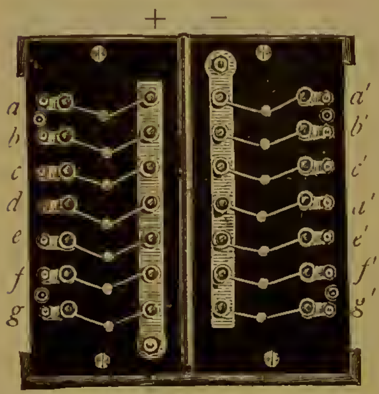


Fig 265.—Fuses fixed in Distributing Box.

Electro-magnetic cut-outs are useful in some cases. They act, in a way easily understood, by the movement of the armature of an electro-magnet, which mechanically breaks the circuit if the current, either drops below, or exceeds a certain value.

Switches.—We pass now to the apparatus used for lighting up or extinguishing any lamp or group of lamps. It is in the ease and convenience of these operations that the superiority of the electric to all other methods of artificial illumination is most manifest. When it is required to light any particular lamp it is only necessary to complete the circuit of which that lamp forms a part. Similarly, on breaking the circuit the lamp is extinguished. The pieces of apparatus by which the currents are made and broken are technically known as "switches." A switch is, therefore, some simple contrivance for bridging or making a gap in a circuit, and it can readily be placed in the most convenient position for the purpose.

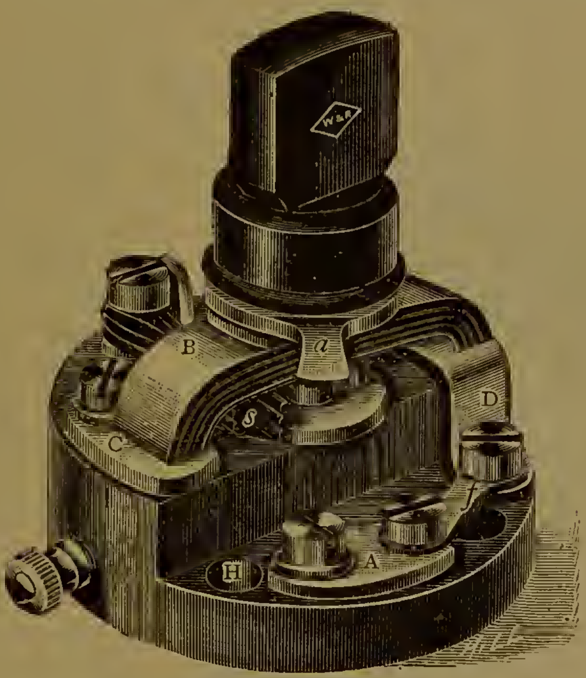


Fig. 266.—The "Diamond" Switch with Cover removed.

Here, again, the conditions are so simple that almost innumerable varieties of switches have been designed, of which we can only illustrate one or two. In designing a switch, one property of the current must not be overlooked, and that is, that on "breaking" a circuit in which a current is flowing, there is usually a spark, and that if the gap be very small a persistent "arc" may be formed. The "break" should, therefore, be effected rapidly, and, since some people are naturally slow in their movements, the switch should be so designed that the rapidity with which the final break is made is independent of the rate at which the handle of the switch is moved. Also, since in any case there will be a spark, the base and fittings of the switch should be incombustible.

These various conditions are well observed in the switch depicted in Fig. 266, and known as the "Diamond" switch, of Messrs. Woodhouse and Rawson. The base of the switch is of porcelain, or some other fairly good insulating material. One of the conductors leading to the lamps under consideration is brought to a convenient position and cut. One of the loose ends is led through the hole, H, and made fast to the screw on the brass block, A. The other end is brought through a similar hole, not shown, to the screw on the block, C. In this switch a fuse, *f*, connects the block, A, to the block, D, but a fuse is not necessary in the switches if there are proper fuses in well-placed distributing boxes. The switch is shown in the "on" position, with the bridge-piece, B, connecting the blocks, C and D, and allowing the current to pass across. To break the circuit, or throw the switch "off," the insulating handle must be turned in a counter clockwise direction. This will bring the projection, *a*, against the bridge-piece, B, which can turn loosely in the central spindle. As *a* presses against B, it forces the latter off the blocks, C and D, but as soon as the friction against these blocks is sufficiently diminished, a powerful spring, *s*, pressing against a pin rigidly connected to B, forces the latter to fly sharply off the blocks, thus securing a very rapid break, the rapidity of the break being independent of the speed with which the handle is turned. The motion of B is arrested by a stop-block at the back, not shown in the figure.

There is one point we must not omit to mention, and that is that the contact between B and the blocks, C and D, is a *rubbing* contact, so that the continual use of the switch tends to keep these metallic contacts bright and clean. All good switches are designed to act in this way.

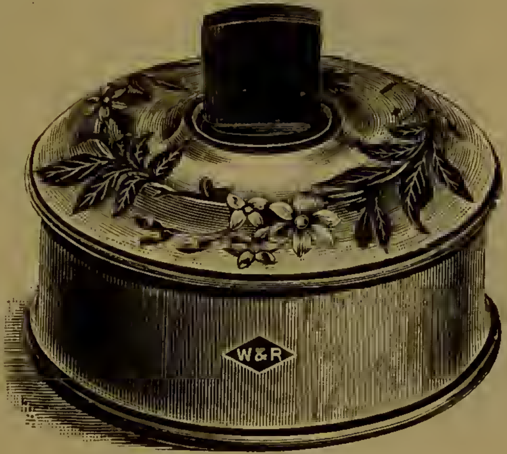


Fig. 267.—Switch with Ornamental Cover.

When in use, the switch is covered up with a cover, which may be made to harmonise with the decoration of the room in which it is, as shown in Fig. 267, which represents a switch with the cover on. It may also be placed in any convenient position, either inside or outside the room in which the lights controlled by it are fixed. As a rule the best position is just inside the opening of the door at a height of about five feet. When so placed, anyone entering the room in the dark can readily lay his hand on the switch, and at once flood the room with light; and, also, on withdrawing, a passing touch is sufficient to again plunge the room into darkness.

A very convenient and useful form of switch for use with movable lamps is shown in Fig. 268. It is usually referred to as a "wall socket and plug," and consists of two parts.

The lower part, or socket, S, is intended to be fixed in the wall of a room near any spot where a temporary light may occasionally be required, such as near the head of a bed in a bedroom, or near the piano in a drawing-room. So placed, its presence may be almost concealed by the decorations near it. Two conductors, from the positive and negative leads respectively, are brought in at the back of the socket, and connected to two hollow brass tubes opposite the openings, A and B. The plug, P, which is connected by flexible leads to some form of hand or movable lamp, carries two split brass pins, *a* and *b*, which can be inserted in the tubes of the socket. These pins are joined one to each of the flexible conductors leading to the lamp, and when they are inserted in the socket the lamp is lit up. As a number of these sockets may be placed in different positions the lamp can be carried about, and lit up wherever temporarily required.

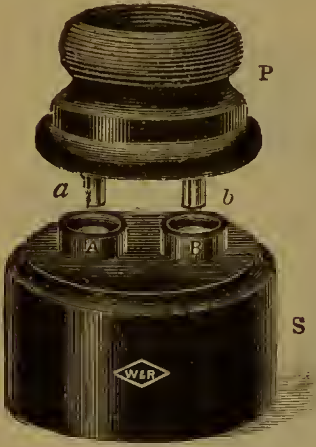


Fig. 268.—Wall Socket and Plug.

Lamps.—We now come to the lamps and their fittings. The almost perfect adaptability of the glow lamp to all purposes of artificial illumination, is, perhaps, most fully displayed in the variety of the fittings designed for use with it. It can be worn in the button-hole or in the hair, plunged under water, or brought near delicate fabrics, such as lace curtains, from which all other kinds of lights have to be kept at a distance. It can hang downwards, or be directed upwards or sideways, at will. For all these, and numerous other purposes, fittings have been designed, which it would be impossible for us even to attempt to describe. They may be either strictly plain and severely utilitarian in their appearance, or highly artistic and decorative, and may be made to harmonise with any surroundings.

When pendent from the ceiling, the holder shown in Fig. 238 is usually surmounted by an opal or other reflector or shade, to cast the upward travelling rays downwards. In this case the lamp can, if required, be made adjustable in height, as shown in Fig. 269, where the flexible conductors, C, C, C, supplying current to the lamp, L, pass over a fixed pulley, P_2, and under a movable pulley, P_1, the latter carrying a counter-balance weight, W. In all cases of hanging lamps special devices have to be used to take all strain off the terminals to which the conductors are attached at the ceiling, for such strains may give rise to bad contacts, with consequent heating and risk. For this purpose carefully-designed "ceiling roses," as they are called, are employed; one of them is shown at the top of Fig. 269.

We conclude by illustrating (Fig. 270) three recently-designed forms of table lamps, which will tend to show the artistic adaptability of the glow lamp. In these it will be noticed that the lamp in A is surrounded by a transparent globe, whilst that in B is covered

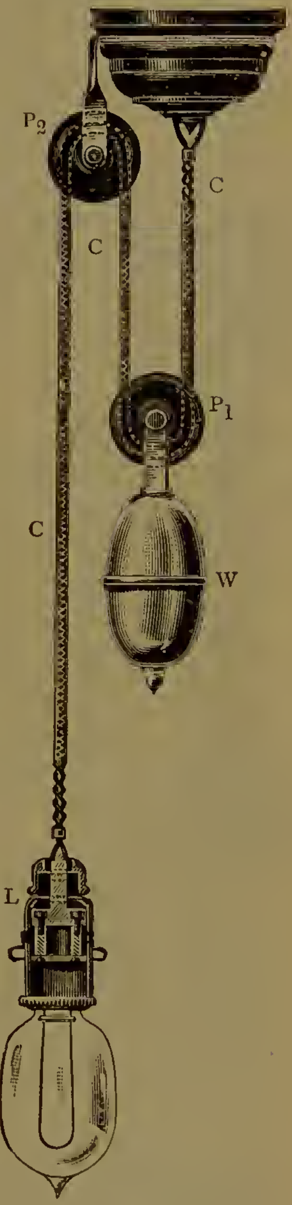


Fig. 269.—Adjustable Hanging Lamp.

with an opaque shade, and in C the lamp is fully exposed. Each stand carries a switch just below the lamp, and the conductors are led up through the central column.

Measuring Instruments.—These have already been fully described in a previous section of the book (*vide* pages 361 and 389). In a private house installation, where the current is generated on the premises, there should be a voltmeter and two ammeters, one for the dynamo current, the other for the lamp current.

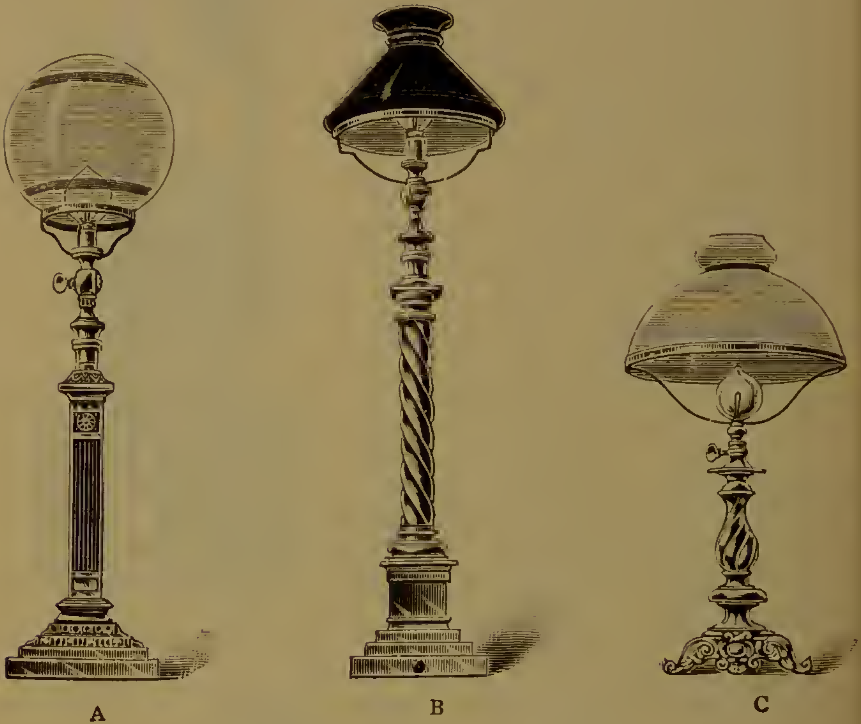


Fig. 270.—Various Forms of Table Lamps.

CENTRAL STATIONS.

No description of electric lighting would be complete without some reference, however brief, to the large generating

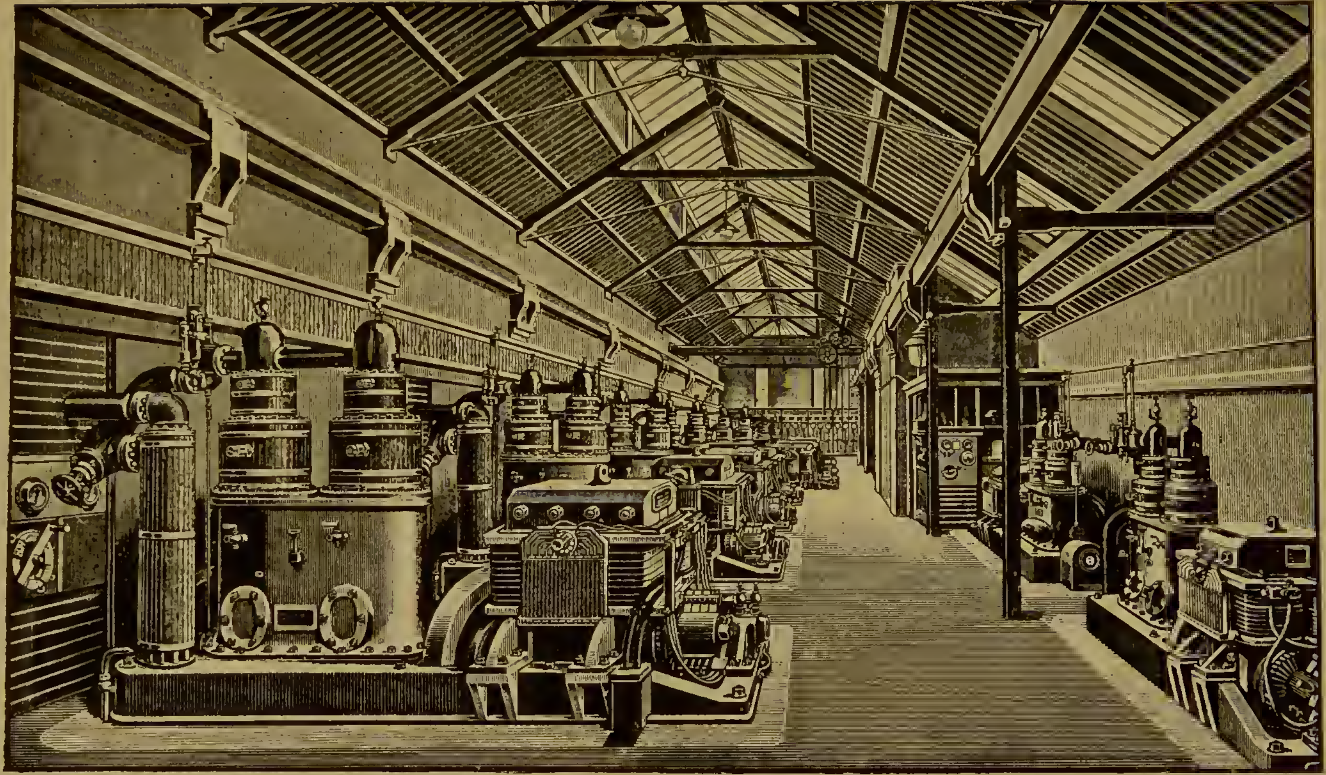


FIG. 271.—CONTINUOUS-CURRENT LOW-PRESSURE STATION.

stations which have been erected during the last ten years for the public supply of electric current energy in all important towns in the civilised world. It is true that many of the details of these stations are only of technical interest to engineers; but the general plan of working, the general methods employed, and much of the apparatus used, have a fascinating interest for a far wider circle. No apology, therefore, is needed for the introduction of some brief remarks upon them here.

We do not propose, just now, to enter into the question of the various methods of the transmission and distribution of the electric current. These methods will be discussed later on. For our present purpose we may classify the different stations into low-pressure and high-pressure supply-stations. The former, as a rule, use continuous current dynamos, with or without accumulators, or secondary batteries. The latter, as a rule, generate alternate currents.

For a typical low-pressure or continuous-current station we illustrate in Fig. 271 the engine and dynamo room of one of the stations of the Liverpool Electric Supply Company. Each dynamo is directly coupled to a Willans compound high-speed engine, and any engine and dynamo can be stopped or started as the exigencies of the demand require. Since a steam engine works much more economically on a full load than on a light load, the object of having so many engines and dynamos is to keep all those that are working at any one time as near full load as possible.

The dynamos are of the two-pole "undertype" pattern, described at page 232, but with this difference: that the field-magnets, instead of being placed upon a solid bed-plate, with a non-magnetic footstep interposed, are suspended by side-brackets, and project downwards into a non-magnetic air space in a bed-plate consisting of a massive iron frame. Some of these dynamos were built by Crompton and Co., and others by Siemens Bros. and Co. There are two sizes. The maximum output of the larger ones is 700 ampères at 110 to 135 volts when running at 375 revolutions per minute, and they are driven by engines capable of developing 180 indicated horse-power. Each of these dynamos could, therefore, supply current to about 1,200 glow lamps, each of 16 candle-power at 100 volts, or to double the number of 8 candle-power lamps. The smaller dynamos can each give one-third of the above output; they are driven at a higher speed, 450 to 500 revolutions per minute, by engines of 60 indicated horse-power. Some of the dynamos are compound-wound,[1] but most of them have only a simple shunt winding on the field-magnets. In all cases an adjustable resistance, fixed, as can be seen, to the side of the dynamo, is placed in the shunt circuit; by altering this resistance the strength of the magnet field, and, therefore, the voltage of the machine, can be varied as required.

An overhead travelling crane runs the whole length of the room, so that, if an accident happens to any dynamo or engine, the damaged machine can be quickly taken to pieces and the injured part replaced by a new part kept for the purpose. This is specially useful when an accident happens to an armature, as a spare armature can then be inserted in a comparatively short time

The switchboard is at the far end of the room, and is not very clearly shown in the figure. We therefore depict in Fig. 272 the essential parts of the switchboard of a continuous-current station, selecting one used by the St. James's and Pall Mall Electric Light Company. In this station the three-wire system, explained at page 659, is used. The upper part of the figure shows the actual switchboard, whilst the lower part gives the details of the connections, which are all made at the back of the board. The letters on the two parts of the figure correspond. There are in all 12 dynamos, 10 of which can each give 1,000 ampères, and the other two 420 ampères each. Two only of these dynamos, one

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[1] *See* page 218.

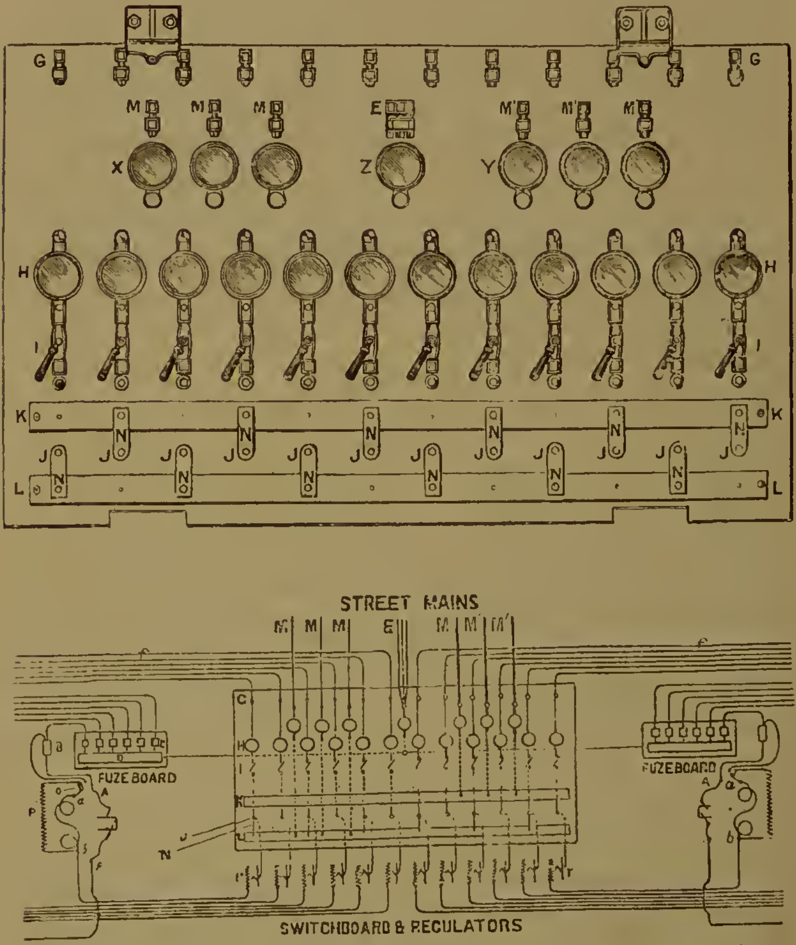

Fig. 272.- Switchboard of a Continuous-current Station and Diagram of its Connections.

on each side, are diagrammatically shown in the lower part of the figure. From one of the terminals, F, of each dynamo a lead, *f*, is taken to a corresponding terminal, G, at the top of the board. From G a thick copper conductor

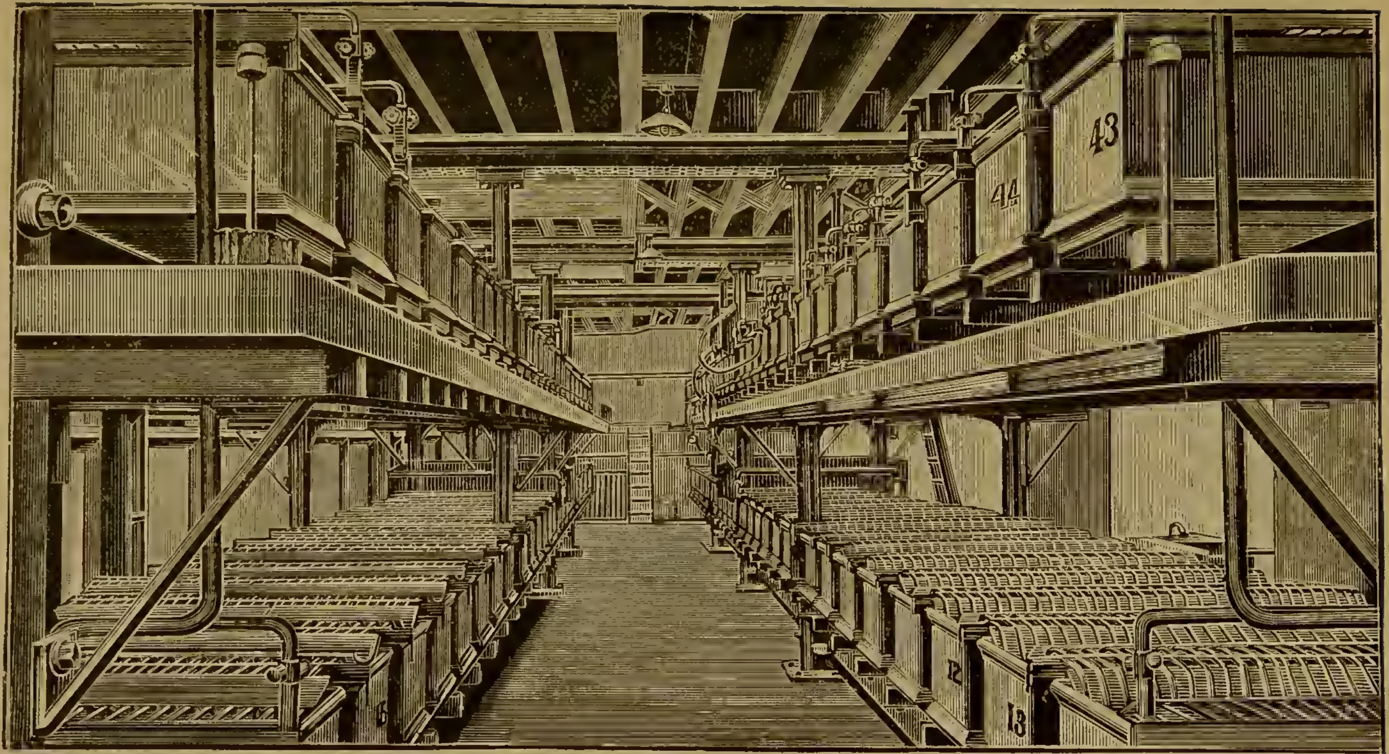

FIG. 273.—A SECONDARY BATTERY ROOM.

leads through an ammeter, H, to the upper contact of a switch, I, the lower contact of which is connected to a stud, J. There are twelve of these studs, one for each machine, placed midway between two massive bars of copper, K K and L L, to either of which any stud can be connected by a thick strap of copper, N. One of the bars, L L, is connected through the three ammeters, X, to three mains, M, which form one side of the three-wire system, and the other is connected through the ammeters, Y, to the mains, M′, which form the other side of the system. The middle or intermediate main, E, is connected through the ammeter, Z, to the other terminals, A, of the dynamos, as shown in the lower figure. Each of these terminals is connected through an electro-magnetic cut-out, B, to a fuse, C, on a fuseboard, D, at the side of the switchboard. After passing the fuse, the current goes into a common conductor for the twelve machines, through Z to E. The electro-magnetic cut-out, B, automatically breaks the circuit if the current from the machine falls below 30 ampères. The current in the field magnets, *a*, *b*, of any machine is adjusted by a resistance, *r*, placed between *b* and the corresponding stud, J.

The switches, I, enable any machine to be thrown into or out of circuit, and by the straps, N, it can be connected to either side of the three-wire system. The ammeters, H, show the current given by each machine, whilst the ammeters, X and Y, indicate the currents respectively on each side of the system, and Z shows the current entering or leaving the station by the intermediate main.

Secondary Battery Sub-Stations.—In connection with most continuous-current stations there are frequently secondary batteries, used either as regulators, to adjust the pressure, or as reserves to take up the load during the hours when the demand is small, and sometimes as continuous-current transformers, for reducing the pressure in a way subsequently explained (*see* page 664).

Such a battery sub-station is depicted in Fig. 273, which represents a battery room fitted up with Crompton-Howell accumulators, and belonging to the Notting Hill Electric Lighting Company. The particular type of secondary cell used has been already fully described at page 82, but for central station work the cells are longer, and contain as many as 61 plates, 30 of them positives, and 31 negatives. Such a cell is capable of discharging at the rate of 500 ampères for one hour, and a battery of 50 such cells fully charged can, if required, supply electric energy at the rate of 60 to 70 horse-power. The room illustrated contains two complete batteries, arranged in two tiers on either side of a central gangway. The cells in one tier are permanently connected together in the manner already described, and the conductors passing from one tier to another and to the switchboard are very massive copper rods or bars. Some of these will be noticed leaving the regulating cells of the top tier on the right hand side. Each cell is mounted on glass insulators, standing on wooden trestles, and all the woodwork in the room is painted with a special acid-proof paint to resist the action of the acid spray with which the atmosphere becomes laden when the cells are being charged.

Alternate-Current Stations.—As a typical high-pressure alternate-current station, we depict in Fig. 274 the dynamo-room of the Sardinia Street station of the Metropolitan Electric Supply Company of London. In this room there are ten Westinghouse alternators of the kind described and illustrated at page 242. The alternators are placed on the first floor of the building, the driving engines, one to each alternator, being on the ground floor below. Each alternator is driven from the fly-wheel of its engine by a belt passing through the floor and carefully boxed in to prevent accidents; in the figure, however, one of the covers has been removed to show the drive. The maximum output of each dynamo when running at 1,000 revolutions per minute is 125 ampères at 1,000 volts, or nearly 170 horse-power. The field-magnets are excited by continuous current dynamos driven by separate engines. There are three of these dynamos, each capable of giving 300 ampères at 100 volts, a current sufficient for the whole of the ten alternators. It will be noticed that the room contains a travelling crane, which can be brought over any of the alternators. Thus, the work of lifting off the upper half of the field-magnets and replacing a damaged armature occupies but a short time. The spare armatures will be noticed standing ready at the far end of the room.

At first sight, the switchboard, which occupies the whole of one side of the room, appears very complicated, but its plan is, in reality, simple. The centre of the board is reserved for the dynamo switches and the measuring instruments and regulating appliances connected with the dynamos. In the lower part of this section of the board are the adjustable resistances, which are placed in the field-magnet circuits of the various dynamos. The three central frames contain the resistances for the field-magnet circuits of the continuous-current dynamos, whilst the other ten—five on either side—contain the resistances for the ten alternators. Each of the latter circuits is controlled by a switch, and has an ammeter in it to measure the current. The two conductors from the armature of each alternator are brought to the board and are provided with switches and safety fuses. One of them passes through an ammeter, to measure the current. The pressure is measured by a voltmeter in the secondary of a small "step-down" transformer,[1] whose primary terminals are connected to the two dynamo conductors. These twenty ammeters and ten voltmeters occupy the upper portion of the centre of the board.

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[1] The construction of alternate-current transformers is described at page 680.

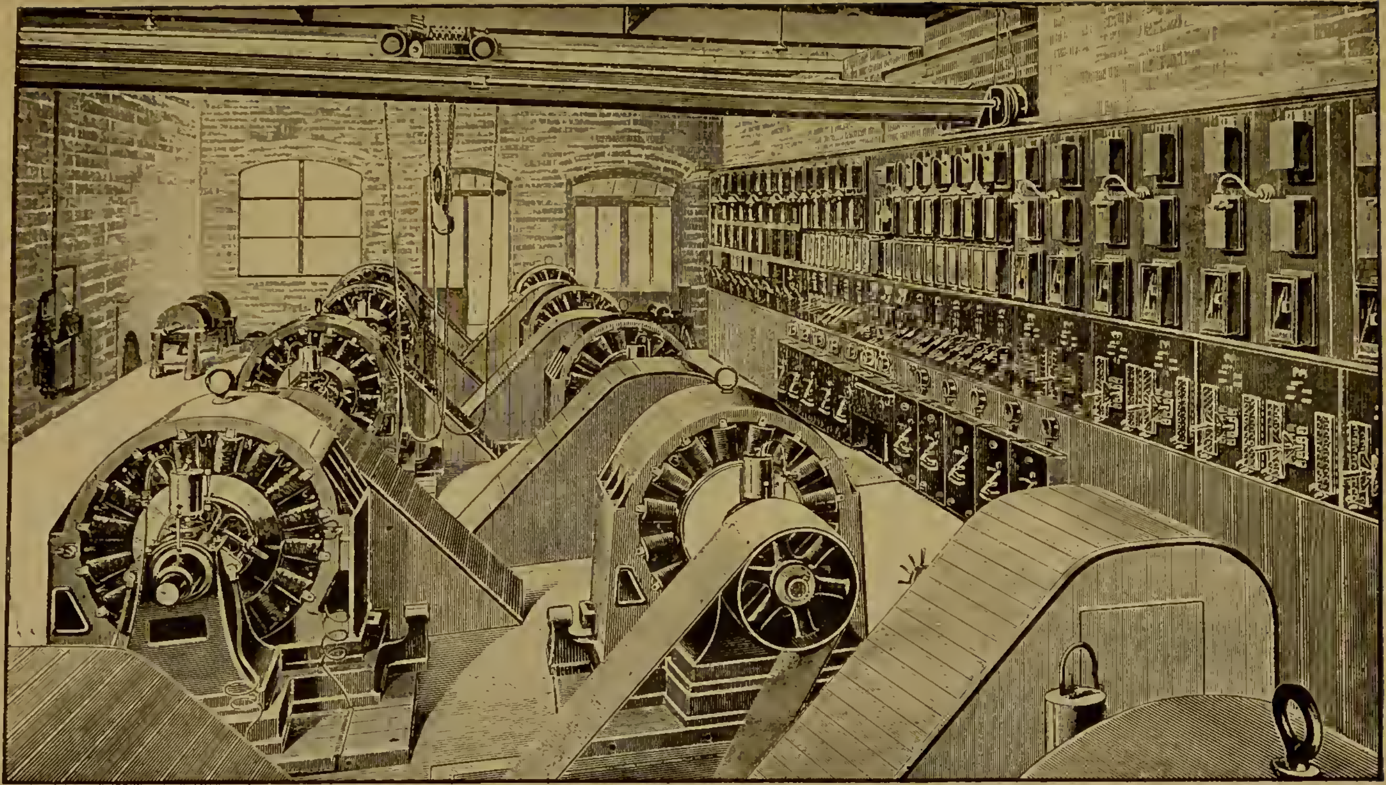


FIG. 274.—ALTERNATE CURRENT HIGH-PRESSURE STATION.

The ends of each pair of feeding or distributing mains are brought to the board on either side of the centre, and both leads of a pair are provided with switches known as "double-pole" switches. One conductor of each pair passes through an ammeter, which measures the current. The dynamos are not run in parallel, but, by simple plug connections, any dynamo can be put on to any pair of mains or distributors, and a change can be made from one dynamo to another with scarcely a perceptible flicker of the lamps.

With this we must conclude our description of Central Stations, passing by many interesting scientific problems which present themselves in their working, but which the space at our disposal will not permit us to enter upon. Later we shall have something further to say about the systems of distribution by which the electric energy generated in the station is conveyed to the ordinary consumer.

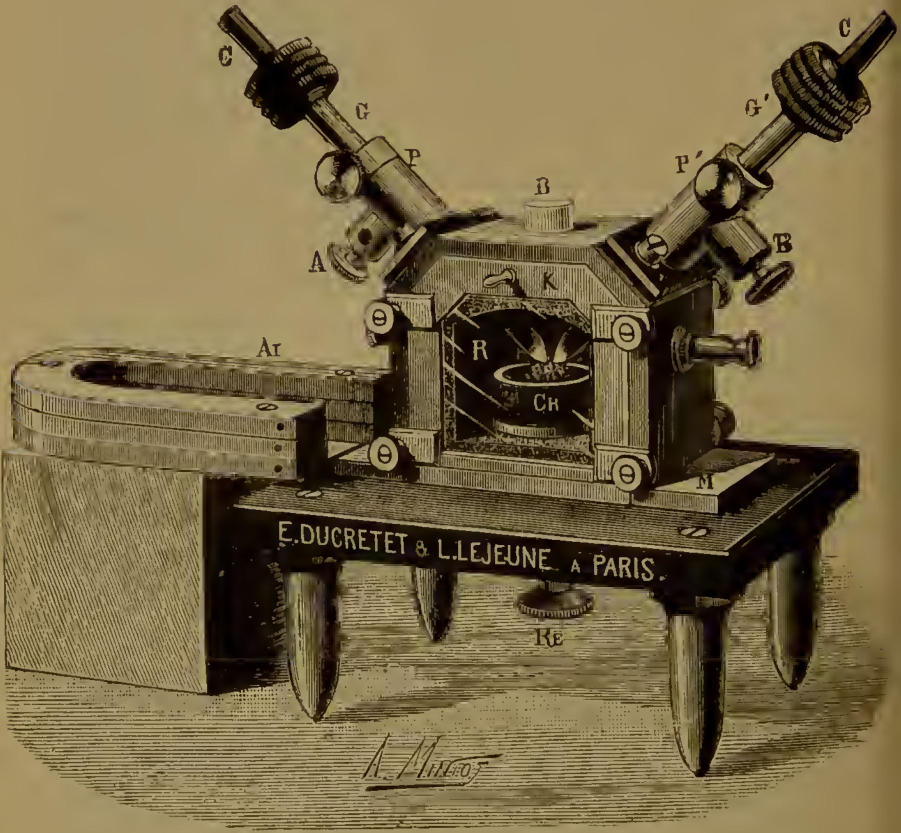
Other Applications of the Heating Effect.

Although the employment of the heating effect of the electric current for purposes of illumination is at present by far the most important of its applications, it is by no means the only one. The great advantages of this method of producing heat are, first of all, the ease with which the heat generated can be concentrated at any desired point, and, secondly, the almost perfect control of the amount generated. Our readers will be, by this time, sufficiently familiar with the properties and uses of the current to recognise that these advantages can easily be secured. We therefore need not stop to discuss again, in detail, the principles on which they depend; but we may proceed at once to the applications of those principles to metallurgical and other purposes.

Electric Furnaces.—The fact that the electric current can convey energy from the outside into an hermetically closed space, and liberate it there in the form of heat, constitutes one of the chief characteristics of electric furnaces. No foreign materials to support combustion require to be introduced into the furnace, and no products of combustion removed. Thus, the materials to be affected by the heat are completely guarded against the action of fuel, whilst the heat is generated in their midst and not outside the vessel containing them. For several important metallurgical operations this is an enormous advantage, and especially in the production of metallic aluminium, to which we shall refer presently.

But not only is the electric furnace available for large metallurgical operations in the arts, it is also of great use to the chemist in many laboratory operations, and this use of the furnace will probably be greatly extended in the future as its advantages and convenience become more widely known.

Such a furnace consists essentially of the electric arc produced in the interior of a suitable crucible containing the material to be acted upon. One arrangement of apparatus for the purpose is shown in Fig. 275. The crucible C R is placed in a small chamber, R, made of refractory material and having a removable screen, K, on one side. This screen for many operations may consist of deep ruby-red glass, through which the changes taking place in the crucible can be watched; but for the highest temperatures a more refractory material, such as talc, must be used for the screen. The carbons, C C′, are inclined at right angles to one another and 45° to the vertical; they can easily be adjusted by hand, and for large currents the carbon holders can be kept cool by a stream of water circulating through them. The chamber R has an opening, B, at the top, by which the materials can be introduced into the crucible, and there are also arrangements for filling the interior with any required gas. The play of the electric arc can be controlled by the magnet, A, which, in some positions, can make it act as a true electric blowpipe. With a current of 12 ampères at 55 volts a temperature of 3,500°C. can be attained, and with it specimens of the rare metals ruthenium and osmium have been procured in sufficient quantities for chemical examination.


C
G
P
B
C
G'
P'
A
B
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Ar
R
CR
M
E. DUCRETET & L. LEJEUNE A PARIS
Re

Fig 275.—Ducretet's Electric Laboratory Furnace.

Turning now to heavier work, one of the greatest achievements of the electric furnace has been the production of the metal aluminium at a sufficiently low price to make it available for many ordinary purposes. The minerals —such as clay, felspar, slate, etc.—in which aluminium exists are very plentiful and widely diffused; but the production of the pure metal from them was so difficult that as late as 1850 its price was £18 10s. a pound. It can now be produced profitably for less than 5s. per lb. It is white, and the lightest of the metals proper, having only one-third the specific gravity of iron and one-fourth that of silver.

Of the various electrical methods used for the reduction of the aluminium ores, the Cowles relies on the heating effect only of the current, whilst others, such as the Hall and the Hérault processes, use both the heating and the electrolytic effect. The former produces chiefly alloys of aluminium, whilst the latter can furnish the pure metal if required.

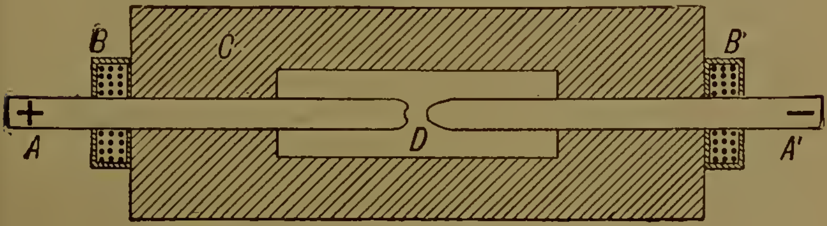


Fig. 276.—Diagram of Cowles' Electric Furnace.

The arrangement of the Cowles electric furnace is shown diagrammatically in Fig. 276. It consists of a fire-brick box, C, enclosing a small inner chamber, D, lined with limed charcoal. Carbon rods, A, A′, project into this inner cavity; good electrical contact for the large currents used is secured by passing the rods through boxes, B B′, filled with copper shot. The charge completely fills the inner chamber, and consists of the ore to be reduced mixed with broken pieces of electric-light carbon to give the mass an initial conductivity. On passing the current the arc is struck between the ends of the carbon rods, and the temperature quickly rises to the point necessary for the reduction. The alloy is drawn off as it is formed from the bottom of the furnace.

In the other processes a somewhat more complicated arrangement of apparatus is used. In the Hérault process the current is passed downwards from a carbon anode through the molten material to a carbon crucible forming the kathode. Alumina, which is an oxide of aluminium, is fed in from time to time, and the pure metal is drawn oft from the bottom of the furnace. Currents of 12,000 to 15,000 ampères are used, and the process is continuous. Mr. Hall uses an electrolytic bath of alumina dissolved in the double fluoride of aluminium and potassium, which is kept fused by the heat evolved.

Electric Welding.—Another operation in which the electric production of heat possesses many advantages is that of welding. It is well known that many metals, of which wrought-iron is a conspicuous example, possess the property of making firm and good joints when the two pieces to be joined are raised to a white heat and hammered or pressed together. Everyone is familiar with the village smithy and the figure of the brawny blacksmith hammering the white-hot iron on the anvil, not to mention the more massive operations in which the Nasmyth steam-hammer is used. Now, in heating the iron to the necessary temperature for a good weld in these old processes, much more iron is heated than that involved in the actual weld, and, moreover, the heating being usually done in furnaces, only a small proportion of the heat of the furnace is really applied to the iron. The great advantage of an electric method is that the heat is produced just at the surfaces to be welded, and that the greatest part of it is usefully employed.

There are two principal methods by which this is accomplished. In one a large electric current is made to flow across the two surfaces to be welded, these surfaces being pressed together by suitable mechanical devices. So great are the advantages of this method that many metals—such as copper, brass, bronze, tin, and others, which cannot be treated at all in the ordinary way—can be firmly welded together electrically. In the other method referred to, the heat of the electric arc is directed on to the two adjacent surfaces that are to be welded together.

Dealing with the methods in the order named, the first requires that the two parts to be joined should be brought together and a large current passed across the junction. By a *large* current we mean one of considerable magnitude. The magnitude of the current required may be gathered from the statement that to weld together two round iron rods one inch in diameter it is estimated that a current of 5,000 ampères is necessary, and rods of double the diameter require about 20,000 ampères. These large currents, however, like those used in electrotyping, need only be of low voltage, and, moreover, are only required for a short time. Thus, the first of the above-mentioned welds only requires the current for 20 seconds, and the other is heated in 80 seconds.

Two different ways of procuring these large currents may be adopted in actual practice. The first consists in using a low voltage and large current dynamo similar to those already referred to in connection with electrotyping and plating. In this case the work is brought close up to the dynamo, so as to avoid the loss of power that would be involved if long leads had to be employed. We do not propose to refer in detail to this method, as the proper dynamos have already been described, and the clamps and apparatus are much the same as are used in the other method.

This other method employs alternate currents, with or without transformers. The latter instruments will be fully described in a subsequent section[1]; for our present purpose

[1] *See* page 680.

it is sufficient to explain that they can transform an alternate current of moderate pressure into a much larger current at a correspondingly lower pressure. Such a welding transformer for small work is shown in Fig. 277. The dynamo current is brought to the transformer by the fine wires, and passes through the windings on the laminated iron ring. The alternating magnetic flux so set up threads through the two coils, C C′, each consisting of a single turn of heavy copper. At A and A′ there are gaps with suitable clamps arranged on each side of the gap in which the pieces to be welded are fixed, and pressed together by the levers. The induced current flows across the joint where, because of resistance, a great amount of heat is generated. The temperature rapidly rises, and, as the metal softens, the clamps are pressed forward until the weld is complete. The process is very rapid, a weld of two pieces of round iron one inch in diameter being

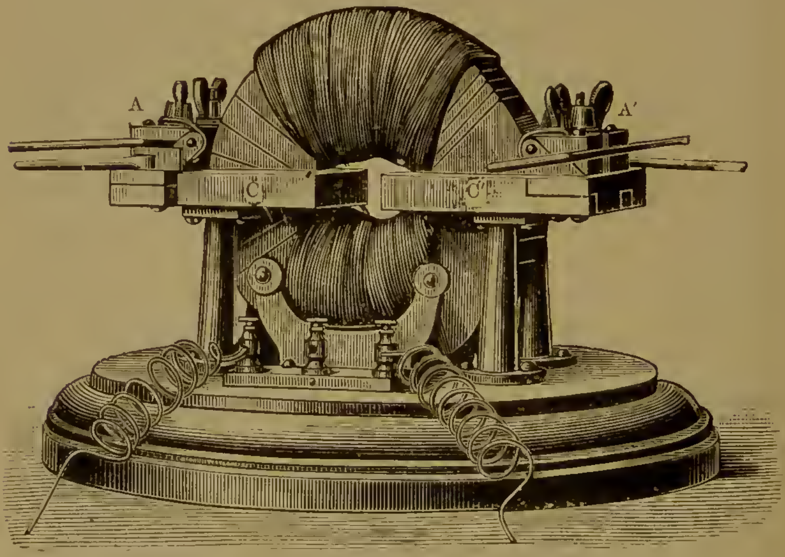


Fig. 277.—Small Electric Welding Transformer.

completed in 20 seconds with an induced current of about 5,000 ampères.

The other process of welding, known as the Bernardo's process, employs the heat of the electric arc. The metals to be welded are connected to the negative main supplying the current, and the positive main is connected to a movable carbon held in the hand of the operator in a suitable holder. A convenient form of holder is shown in Fig. 278. The conductor passes through a wooden handle, A, in front of which is a protecting sheet-iron screen, S; at the other end the carbon is held in a metal clamp, to which the conductor is connected. The carbon is moved over the surface of the materials to be welded and a powerful arc struck quickly raising the temperature to the welding or fusing point. The method of using the arc to weld two upright plates is shown in Fig. 279. In this case the metal is actually melted and is confined whilst fluid by the carbon blocks, C′ C″.

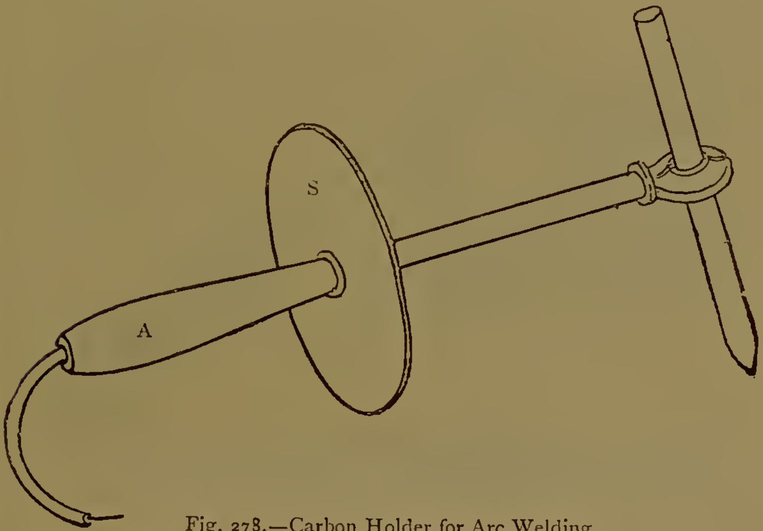


Fig. 278.—Carbon Holder for Arc Welding.

Blasting, etc.—The last application of the heating effect we can notice is that in which an *electric fuse* is used for igniting gunpowder, dynamite, or other explosives, from a safe distance, either for industrial or warlike purposes.

Instead of employing a slow-burning match or fuse, with all the dangers and uncertainties that accompany its use, the igniting arrangement consists of a small quantity of gunpowder in a tube. Imbedded in the powder are the ends of two copper conductors brought close together and joined by a piece of fine platinum-silver or platinum-iridium wire. Copper conductors are connected, through suitable terminals, to flexible leads which can be continued to the battery and switches at a safe distance. On passing the current, the little bridge of platinum-silver wire is made white-hot and ignites the powder, which, in its turn, fires the full charge for the blast. Such fuses can obviously be used for submarine mines, and in other cases, where ordinary slow fuses are out of the question.

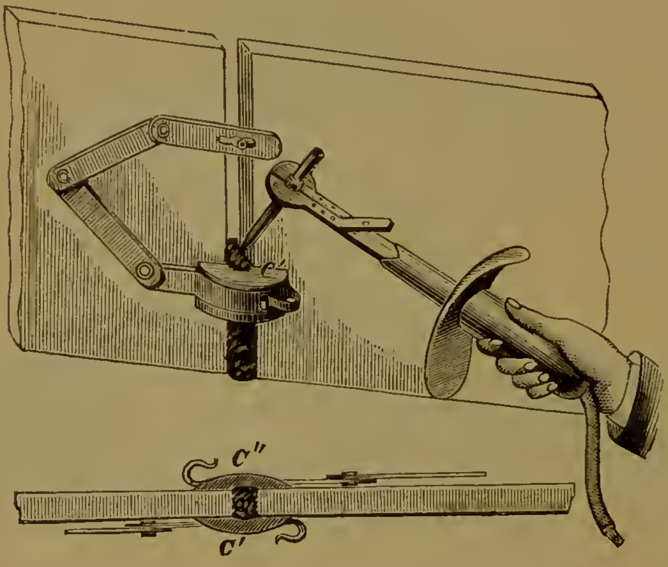


Fig. 279.—Electric Welding of Two Iron Plates.

CHAPTER XIII.

APPLICATIONS OF THE MAGNETIC EFFECT.

However interesting and splendid the applications of the Thermal effect of the electric current may be, they have not as yet become of such enormous social or financial importance as the applications of the Magnetic effect, though in process of time it is possible they may rise to an equal, if not to a higher, position.

We have briefly referred in our introductory lines to some of the profound changes which the development of the electric telegraph has wrought throughout the social fabric of modern life, and the spread of telephonic communication is even now intensifying and consolidating those changes. Whether the changes have brought with them a substantial addition to the sum total of human happiness, it is not for us to discuss here, though we may freely admit that the blessing has not been an unmixed one. But turning from the social to the scientific aspect of the question, no thoughtful man can be blind to the wonderful results that have been achieved—results which, throughout the limits of this small earth of ours, have almost succeeded in annihilating time and space in placing man in communication with his fellow-men, and which, in this respect, have outstripped the wildest dreams of even the poets of former ages.

At present, not only socially and scientifically, but also in the amount of capital invested and in the numbers who find employment therein, the electric telegraph takes precedence of all the applications of electricity to the service of mankind. That this is the case will be admitted when we state that the total length of the land-lines constructed to the end of 1891 was 2,002,402 miles, and the submarine cables at the same date were 164,610 miles long. The money value of these land-lines is estimated to be over 60 millions sterling, and the amount of private capital embarked in cable-work was over 36 millions, exclusive of the value of the cables owned by various Governments. These figures far exceed anything that electric lighting can, as yet, approach.

In dealing with the applications of the magnetic effect, we shall first treat of the electric telegraph, and then pass on to the still more wonderful achievements of the telephone; after that there will only remain some minor applications—not, however, unimportant in their way—such as electric bells, fire and burglar alarms, electric time-keeping, and so forth.

The Electric Telegraph.

Historical.—It may surprise some of our younger readers, who have not in their lifetime witnessed the rapid development of the last fifty years, to be told that the whole history of electric telegraphy is to be sought within a period of less than one hundred and fifty years. Even those apparently ubiquitous inventors, the Chinese, have not been able to put in a claim that in this direction they forestalled the outer barbarians by a few odd thousands of years. Thus the triumphs of the telegraph can, without fear of contradiction, be entirely ascribed to Western civilisation, science, and enterprise.

Short, however, though the time is, it is not so easy as might be supposed to discover the history of the earliest attempts to communicate over long distances by the aid of electricity. This is due to the fact that these attempts did not attract much, if any, notice at the time, and that the records are, therefore, often buried in unknown and non-scientific publications.

The first actual attempt on record was made by an experimenter who described his method in an anonymous letter, dated the 1st of February, 1753, and published in the *Scots Magazine*, in Edinburgh, over the initials "C. M." There is very little doubt now that the writer of this letter was Charles Morrison, of Greenock, and that his desire to conceal his identity was due to the fear that his neighbours should attribute his experiments to witchcraft. Indeed, he does not seem to have thus disarmed his fanatical and bigoted friends, for eventually he was compelled to emigrate to the New World, it is supposed to escape their persecutions.

"C. M.'s" method consisted in connecting two places by twenty-six separate wires, one for each letter of the alphabet. These wires were supported on suitable poles and insulated with jeweller's cement. The ends were placed in convenient positions for being separately electrified by means of a frictional machine when sending a message, and when receiving a suspended ball connected to each wire was so placed that on electrification it attracted a piece of paper on which a letter of the alphabet was inscribed. By the successive risings of the different pieces of paper a message could be spelled out. Various devices to facilitate the working were also described in the letter.

During the eighty years that followed "C. M.'s" letter to the *Scots Magazine*, various proposals were made from time to time with the view of utilising electricity for purposes of communicating between distant places. Before Volta's discoveries the only means available were sudden discharges sent along conductors from frictional electrical machines or from Leyden jars. In 1774 Le Sage, of Geneva, and in 1795 Salva, proposed that the different conductors should be made up into a cable instead of being kept apart as in

" C. M.'s" experiments. In 1787, however, Lomond showed that the twenty-six wires might be reduced to one. Chappe, the inventor of the semaphore telegraph, tried a system of electric telegraphy, but the most practical attempt with the above means was made by Sir Francis Ronalds in 1823; and we regret that we have not space to describe Ronald's telegraph in detail. He used the discharges from a cylindric electric machine, which he sent through a wire enclosed in thick glass tubes and laid in wooden troughs. At the distant end these discharges caused a pair of pith balls to diverge at the instant when two synchronously moving dials at the two ends exposed the required signal. The chief practical difficulty in all these attempts was that of insulation. The currents used were of such high voltage that the insulation of the conductors was speedily broken down.

But Volta's and Galvani's discoveries placed at the disposal of the inventor a low voltage current which could be maintained at pleasure for an indefinite period of time. Accordingly we find that as early as 1800 Salva proposed to use galvanic currents for signalling purposes. As yet, however, all the properties of the current had not been discovered and investigated, and accordingly Salva employed as his receiving apparatus frogs' legs, prepared and connected up as in Galvani's classical experiment. Later (1809), when the chemical effect of the current was better understood, Sommering invented the electrolytic telegraph, shown in Fig. 280. The current was obtained from the Volta Pile seen at the back; the sending instrument on the right was simply a convenient arrangement of twenty-seven contact pieces, by which the coil could be connected up in circuit with any pair of the twenty-seven wires by which it was joined to the receiving instrument on the left. Each contact piece had a particular letter or sign marked opposite to it, and each wire ended in a gold pin fixed in the bottom of a glass box containing acidulated water. When a current was sent along any particular pair of wires, hydrogen and oxygen were liberated at the respective pins, and thus the signal was indicated. With this apparatus Sommering telegraphed through wires 2,000 feet long, but, for obvious reasons, it never came into practical use.

The discovery of the magnetic effect of the current by Orsted in 1820 entirely changed the aspect of the question; but still it was not until thirteen years later that a practically successful result was obtained. Ampère in 1820, Fechner in 1829, and Ritchie in 1830, successively attacked the problem, but did not produce anything practical; they each used separate circuits for each signal that had to be transmitted. Schilling in 1832, using Schweigger's Multiplier

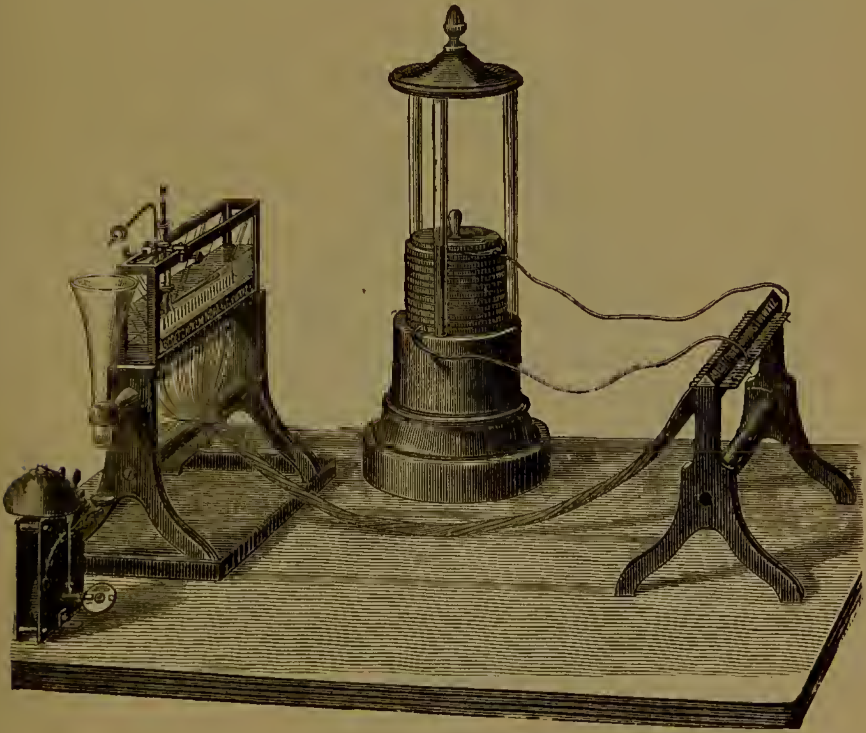


Fig. 280.—Sommering's Electrolytic Telegraph.

(page 338), and only a single metallic circuit, was much more successful. The different letters were indicated by different combinations of the movements of the needle of the multiplier to one side or the other, and thus Schilling's Telegraph was not only the forerunner of the needle instruments afterwards so extensively used, but also of the now widely-known Morse code.

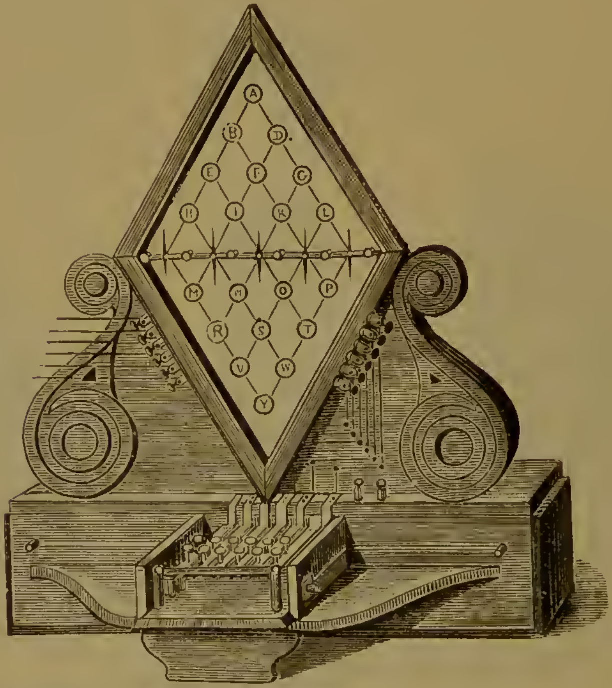


Fig. 281.—Wheatstone and Cooke's Five-Needle Telegraph.

Gauss and Weber (1833) still further developed Schilling's Telegraph; they replaced the light needle of the multiplier by a heavy suspended magnet nearly four feet long. This magnet had a mirror attached to it, the movements of which were observed by means of a telescope and scale; and thus this telegraphic device was the precursor of the much more sensitive "mirror" galvanometers already described.

The year 1837 marks an important epoch in the development of electric telegraphy. Simultaneously and independently in three different countries practical solutions of the problem were worked out. The honour must, therefore, be shared between Wheatstone and Cooke in England, Morse in the United States, and Steinheil in Germany.

Wheatstone and Cooke's first telegraph is represented in Fig. 281. Five circuits were employed, in each of which was placed a galvanometer coil and a break-circuit key. The keys can be seen at the front of the apparatus, but the coils are at the back, and each surrounds one needle of an astatic pair (page 339) of which the other needle is seen at the front. The astatic needles are on pivoted axes, and are weighted so that each pair stands vertically when no current is passing through its coil. On the passage of a current through any coil, the corresponding needle deflects to one side or the other, and by the simultaneous movement of two needles any particular letter is indicated as shown on the diamond-shaped dial. An instrument of this kind was placed at each end of the line, and the signals were, therefore, made simultaneously at both places. The great disadvantage of this apparatus was that it required five wires for each complete line, and thus was somewhat costly. The London and Birmingham Railway used it over a distance of 1¼ miles, and the Great Western constructed a line 39 miles long, but would not incur the expense of a longer one.

Wheatstone's great difficulty at first was to construct electro-magnets which could be worked through long circuits. The law of the electro-magnet (given on page 105) was not then generally known, though in all its essentials it had been discovered by Professor Henry in the United States in 1831. An electro-magnet was usually constructed with any gauge of wire that happened to be at hand at the moment, without reference to the current available for exciting it. The true law appears to have been pointed out by Henry himself to Wheatstone, whom he visited at King's College in April, 1837, and after that the above difficulty ceased to be troublesome.

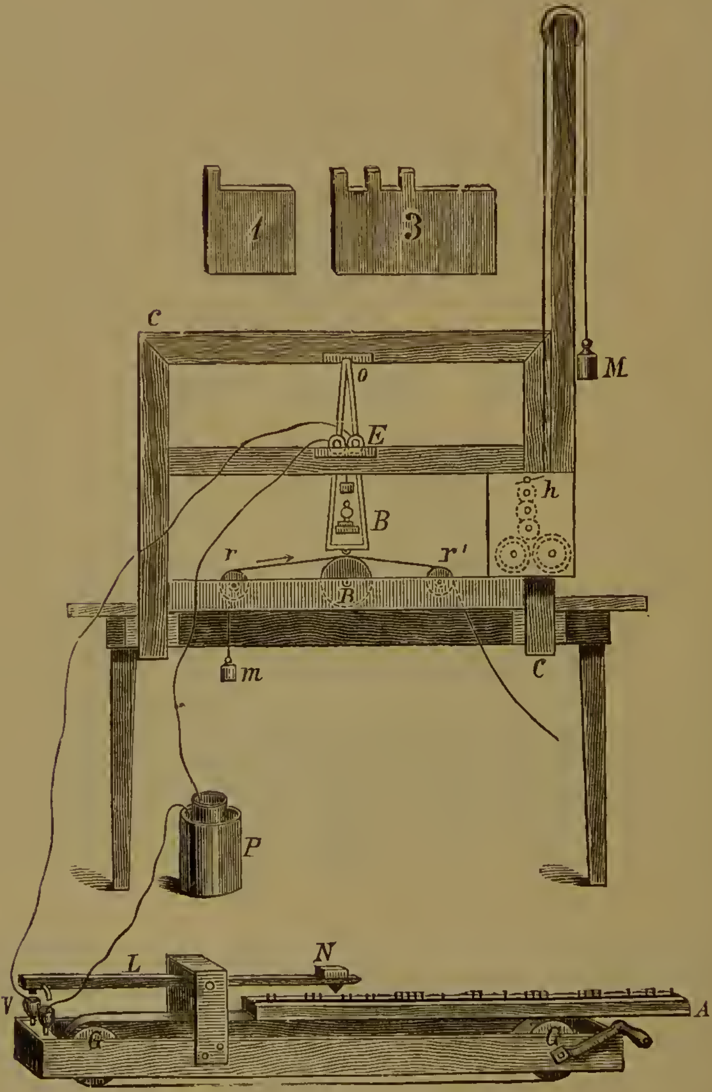


Fig. 282.—Morse's First Telegraph.

The signals in Wheatstone and Cooke's telegraph were not automatically recorded by the apparatus. Morse, taking up a different line of development, attempted from the first to produce a record of the message received. His earliest successful apparatus is shown in Fig. 282. It consisted of an electro-magnet E mounted on a framework *cc* fixed to the table. The armature of the electro-magnet was attached to a pendulum *o*B, suspended at *o* and carrying a pencil at its lower end. Underneath this pencil a paper ribbon was drawn over the rollers *r*R*r*′, by means of the clockwork *h*. When the pendulum was at rest, the pencil simply traced a straight line on the paper; but whenever it was jerked to one side by the pull of the electro-magnet, the line became zig-zag. The sending instrument used to produce the pre-arranged signals is shown at the lower part of the figure. A pivoted lever LN was weighted at one end, N, and at the other carried a spanner, which, when that end was depressed, completed the circuit by connecting the two mercury-cups V. To raise the end N of the lever, and so depress the far end, a series of metal types of the shape shown at 1 and 3 were set in a frame, and were passed underneath a projection below N, thus raising the lever and alternately making and breaking the circuit at V. In this way the pendulum *o*B was alternately attracted and released, and a zig-zag line written on the paper *r*R*r*′. At first, Morse used nine types, representing the first nine figures, 1–9, and he constructed a code, according to which different combinations of the figures were to represent different words. Later, this was replaced by the well-known Morse code, which we shall refer to presently. A specimen of the writing of this machine is given in Fig. 283. The numbers mean, according to the code, "Successful Attempt with Telegraph, September 4, 1837."

In Steinheil's apparatus, instead of battery currents, induction currents were employed, which were obtained by moving a pair of coils past the poles of a powerful magnet, and the apparatus was so arranged that a current could be sent in either direction at pleasure. At the receiving end these currents, passing through a coil, acted upon one or other of two balanced magnets, causing the magnet moved either to strike a bell or make a mark on a moving ribbon of paper. The strokes on the bells or the marks on the paper represented certain letters according to a pre-arranged code.

The greatest service that Steinheil rendered to telegraphy was the discovery of the possibility of using the earth as the return part of the circuit. Previously double wires at least had been thought necessary—one to convey the current to the distant end, and the other to bring it back. Steinheil discovered that one of these wires could be dispensed with by connecting the two points of the circuit between which it should pass to large plates sunk in the earth. The earth, being a conductor, acted instead of the return wire, for, although the materials of the earth are not as good conductors as copper or iron, the low conductivity is compensated for by the enormous mass of the conductor. In fact, both calculation and experiment show that the resistance of this return path is very small, being independent of the distance apart of the earth-plates, and only depending on their size and the continuity of their conducting connexion to earth. This is a most curious result, as is also the additional one that, however many earth returns are being used by different circuits at the same time, each current finds its way back to its own battery.

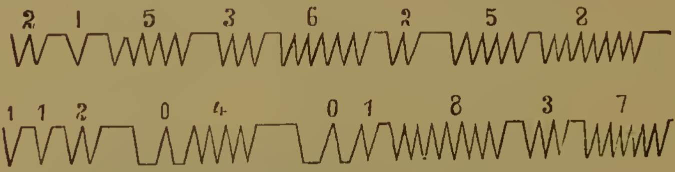


Fig. 283.—Morse's First Written Message.

The above, the first early successful attempts at electric telegraphy, were made in 1837. During the intervening years great improvements in details have been introduced, without which the telegraph could not have been a commercial and social success. Though interesting, it would be tedious to follow these improvements step by step, and we therefore propose now to omit the intervening period, and to describe a few of the more important and widely-used modern systems and instruments.

Modern Overland Telegraphy.

The fundamental principle upon which the working of all modern electric telegraphs depends is extremely simple. The reader is already familiar with the fact that, although the necessary electric pressure be present, no electric current will flow unless a complete conducting circuit be provided. A short non-conducting gap in *any part* of the circuit will prevent the flow of the current, and therefore prevent the production of its characteristic effects in *any other part* of the circuit. In order to communicate between two distant points, we have, therefore, only to arrange at one of these points a suitable apparatus for making visible some effect due to the current, and provide a complete conducting circuit between the two points containing a suitable source of electric pressure. If, then, a short gap be arranged at the other point, which can be opened or bridged at pleasure, a series of signals can be produced at the distant place, which can be combined into an intelligible message according to any pre-arranged plan.

The particular effect now almost universally employed to indicate the opening and the closing of the circuit at the sending end is the magnetic effect, in some one of the numerous forms in which its presence can be made apparent. Practical systems of telegraphy in which the chemical effect is employed have been devised, and some of them rather extensively used; but these are now almost entirely superseded.

Notwithstanding the extreme simplicity of the fundamental principle, the ever-increasing requirements of modern telegraphic intercourse have led to the elaboration and construction of many beautiful and some complicated pieces of apparatus and systems designed to satisfy these requirements. The opening and closing of the circuit at the sending end may be accomplished by hand, various patterns of "keys" being used, or by simple mechanism, the latter being exclusively employed where high speed is required. Similarly, the receiving instruments may give visual or aural signals which are not recorded, or the message may be recorded in pre-arranged characters and read off subsequently. In high-speed working only recorded messages can be received, as the signals are far too rapid to be followed either by the eye or the ear. Lastly, various systems of arranging the transmitting and receiving instruments have been devised in the interests of increased economy or increased speed of working; these will be most conveniently described separately.

The Code.—The various instruments and systems will be more easily understood if the details of the signalling code most often used are first explained. It has been already pointed out that Schilling was the first to show that *two* distinctive signals only are required to produce by their combination a code available for all the purposes of telegraphy. The code now universally followed is, however, not that proposed by Schilling, but one subsequently arranged by Morse. In devising it, Morse, by an elaborate analysis, arranged the letters of the alphabet in the order of the frequency with which they recur in sentences of good standard English. He then assigned the shortest signals to the most frequently recurring letters, so that the messages might, on the average, be transmitted with the fewest number of independent signals. In the following table, showing the "Morse Code," the two distinctive signals are represented by short strokes (or *dots*) and long strokes (or *dashes*) :—

a	. —	p	. — — .	4	. . . . —
b	— . . .	q	— — . —	5	. . . . .
c	— . — .	r	. — .	6	— . . . .
d	— . .	s	. . .	7	— — . . .
e	.	t	—	8	— — — . .
f	. . — .	u	. . —	9	— — — — .
g	— — .	v	. . . —	0	— — — — —
h	. . . .	w	. — —	.	. . . . . .
i	. .	x	— . . —	?	. . — — . .
k	— .	y	— . — —	;	. — . — . —
l	. — . .	z	— — . .	:	— — — . . .
m	— —	1	. — — — —	!	— — . . — —
n	— .	2	. . — — —		
o	— — —	3	. . . — —		

On examination, it will be found that no single letter has more than four signals assigned to it, that figures are denoted by five signals, and marks of punctuation by six.

The above code is applicable wherever two distinctive signals can be produced and observed, and is very widely used for other purposes than those of electric telegraphy. Thus it is employed for flag-signalling for military purposes in the field, for the "heliograph," which commands a longer range, for semaphore signalling between the vessels of a squadron, and also in other directions.

The Transmitting Instruments.

To transmit an electric signal the simplest method is to open or close a circuit containing a battery and a receiving instrument of some kind. To do this a key of the simplest description is all that is necessary, and the working conditions are amply fulfilled in a key invented by Morse himself, and widely used.

The Morse Key.—One form of this key is illustrated in Fig. 284. It consists of a straight metal lever *bb'*, provided with a handle G, and rocking about an axle DD'. At the back end of the lever is a contact point resting on a knob *c* projecting from a slab N of brass. The contact point can be adjusted by the screw S and the lock-nut *s*. This point is always brought into contact with *c* by the pull of a spring *f* whenever the handle G is released. Another contact piece is fixed on the under-side of the lever near the handle, and when the latter is depressed, strikes against a projection *a* fixed on the brass block V. The axle DD' is

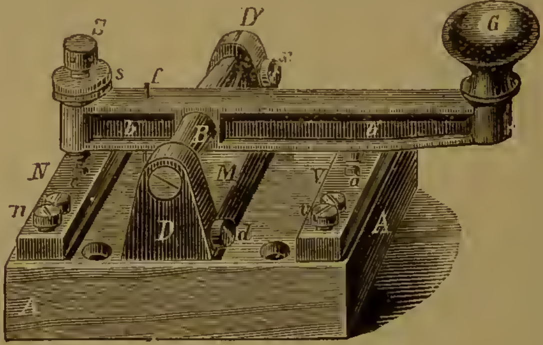


Fig. 284.—A Morse Key.

mounted on a third brass block M, and wires to connect the various blocks to the telegraph lines or the instruments, as may be required, can be attached to the screws *n*, *d*, and *v*. It therefore follows that, when the handle G is depressed, the wires attached to the blocks M and V are electrically connected through the axle DD', the lever *bb'*, and the contacts at *a*. On the other hand, when G is released, the wires attached to M and N are in electrical communication.

THE DOUBLE-CURRENT KEY.—In some systems of telegraphy which are largely used in this country the key is required, when sending a signal, to *reverse* a current which is already flowing on the line. This method, known as *double-current working*, requires a more elaborate key, one form of which is shown in Fig. 285. The working contacts

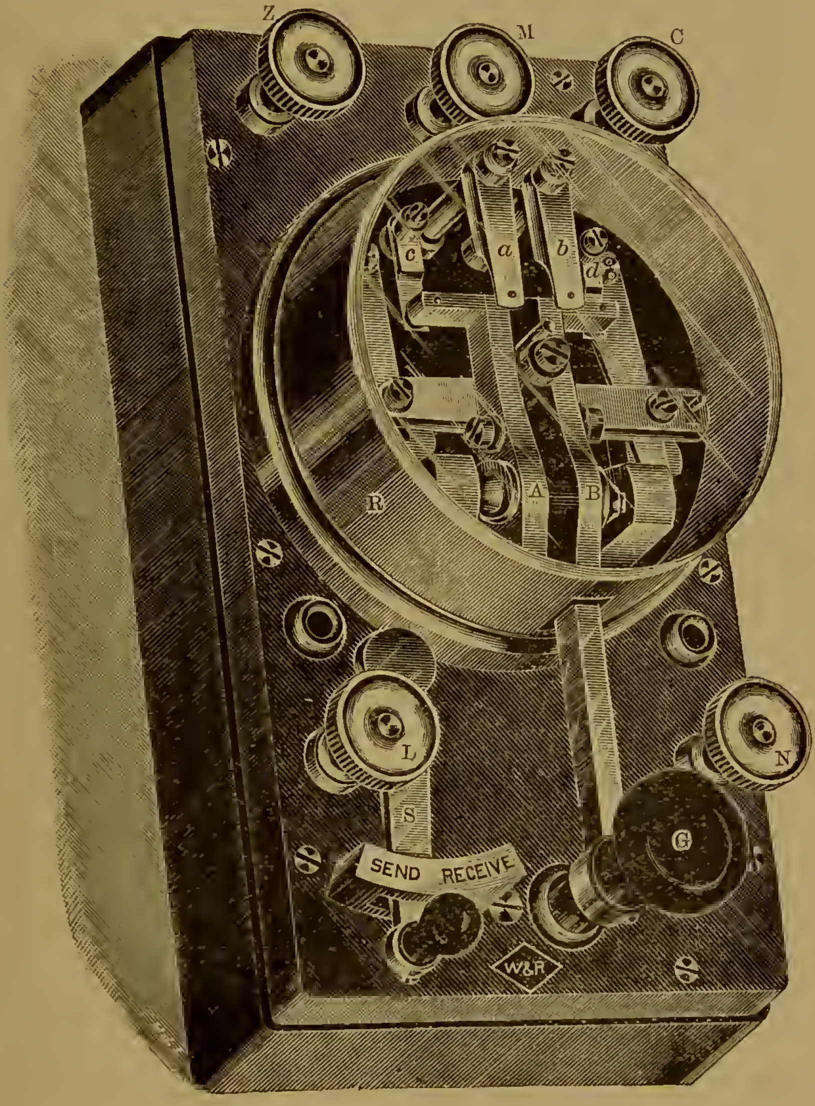


Fig. 285.—A Double Current Key.

of the key are protected from dust and injury by a short brass cylinder R, closed at the top by a sheet of glass. The movable levers consist of two brass pieces A and B, mechanically connected together, and forming a single lever, but electrically insulated from one another by a block of ebonite placed between them. At the back of the enclosing cylinder there are four posts—two long ones placed centrally, and carrying contact springs *a* and *b*, which project over contact points on A and B; and two short posts, one on either side of the others, and carrying brass blocks *c* and *d*, on which two short arms, projecting at right-angles from the ends of A and B, rest. Contact is made on these lower blocks when the handle G is at rest, the levers being held down on them by a spring; but when G is depressed, the lever contacts are transferred from *c* and *d* to *a* and *b*. The contacts *a* and *d* are electrically connected to one another and to the binding-screw Z by wires underneath the base-plate; *b*, *c*, and C are similarly connected. The wires from the battery are brought to the screws C and Z, whilst the two ends of the circuit into which currents have to be sent are brought to the front binding-screws L and N. In the front of the key there is a lever S, which can be moved horizontally. When this lever is moved to the side marked "Send," it operates a switch, which electrically joins the binding-screws L and N respectively to the levers A and B. With S in this position, therefore, when the key is at rest, the screw L is connected through A and the contact *c* with the positive pole of the battery joined to C; whilst N is connected to the negative-pole through B, *d*, and Z. A current, therefore, flows through the outer circuit from L to N. On depressing G, the connections of L and N to the battery are reversed. L becomes joined to Z, the negative terminal, through A and *a*, whilst N is joined to C, the positive terminal, through B and *b*. The current now flows in the opposite direction—*i.e.*, from N to L. Thus, when the lever G is depressed, the current between L and N is reversed, and the required signal is sent.

When the switch S is moved to the side marked "Receive," the levers A and B are disconnected from L and N, so that the depression of G produces no effect on the circuit. But simultaneously N is directly connected to the fifth binding screw M, to which the wire going to the receiving instrument is made fast. A current, therefore, arriving at N from the distant station passes on through M to the receiving instrument without going through any of the movable contacts of the key.

We have described the above key in detail in order that our readers may have some idea of how the simple Morse key has to be modified to suit special requirements. Space would fail us to describe all the varied keys used for transmitting signals *by hand* in the different systems employed. On the design of these a great amount of mechanical as well as electrical knowledge has been expended, and the instruments produced are interesting from more points of view than one. Other kinds of transmitters, to be described later, are used in those systems in which the receiving instrument prints the message in ordinary type instead of the conventional signals of the Morse code. A brief space must, however, be devoted here to descriptions of the mechanical transmitters by which the highest speeds attained in modern telegraphy have been rendered possible, and which can send 600 words, or about 8,000 or 9,000 separate signals, per minute. As about 40 words per minute is quick sending for hand transmission, the above figures show how much more rapid is the mechanical method.

The Quick-Speed Automatic Transmitter.—By the transmission of a telegraphic message mechanically, we mean that the various changes, necessary to the production of the desired sequence of currents, are made by automatically-acting apparatus. More than one system of accomplishing this has been devised, but by far the best known and most widely used is undoubtedly that invented originally by Wheatstone and gradually improved from time to time by others.

The process of transmission is divided into two stages—

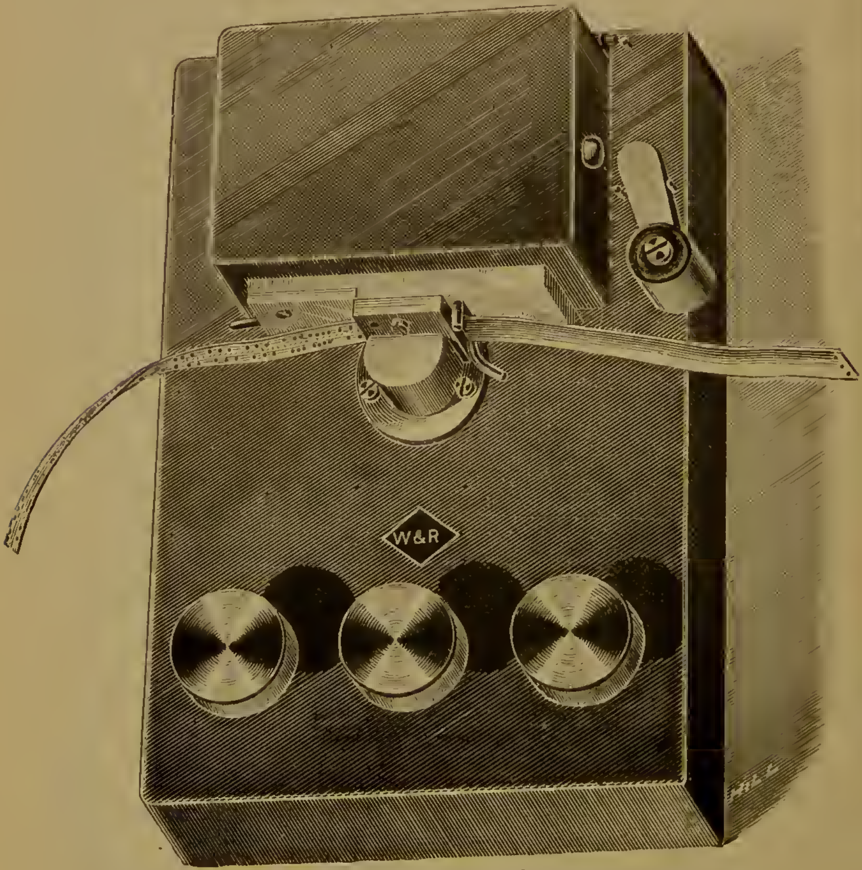


Fig. 286.—The Perforator.

(1) the preparation of the message; (2) the actual transmission. The preparation of the message consists in perforating a strip of stout paper in such a manner that when passed through the transmitter the desired electrical changes are made. The instrument used for punching the strip is shown in Fig. 286, and a slip ready punched in Fig. 287.

The central row of holes in Fig. 287 is for the purpose of drawing the paper ribbon through the transmitter, whilst the holes on either side constitute the message. The perforator (Fig. 286) is provided with three sets of punches worked respectively by the depression of the three keys in front. One of these keys punches a single central hole which causes an interval between the signals preceding and following it. The second key punches three holes in a vertical line thus :—$\begin{smallmatrix}\text{o}\\\text{o}\\\text{o}\end{smallmatrix}$, and these cause the transmission of the signal for a "dot" to the distant station. Finally the third key punches four holes arranged thus :—$\begin{smallmatrix}\text{o}\\\text{oo}\\\text{o}\end{smallmatrix}$, which cause the transmission of a "dash." Thus any combination of dots and dashes representing a letter, etc., on the Morse code can be transmitted.

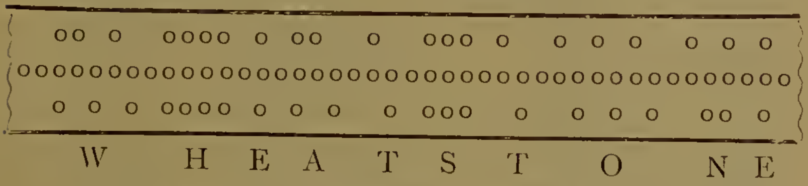


Fig. 287.—Punched Strip ready for sending Message.

In Fig. 288 is shown a diagram of the chief working parts of the ingenious piece of apparatus which acts as a transmitting key when the punched ribbon is passed through it. A little wheel W, driven by clockwork contained in a case behind, carries a series of spokes which engage in the central row of holes in the perforated slip and draw it through at any desired speed. Two vertical rods S and M, attached to the ends of the levers A and A′, are pressed upwards by the tension of the springs s_3 and s_4. These rods are so placed that M comes opposite the upper row of holes in Fig. 287, and S opposite the lower row; consequently when a hole in either of these rows comes opposite the end of a rod, the rod can be pressed through by the action of the springs. Both rods, however, are not free to move up at the same time, their motion being controlled by a beam Y rocking about its centre and carrying two pins P and P′ which bear on A and A′. This beam is kept vibrating uniformly by the same clockwork that drives W. Tracing the levers backwards, we see that the upward motion of S will cause the rod HK to move to the right, and that of M will move H′K′ to the right. These latter rods act on

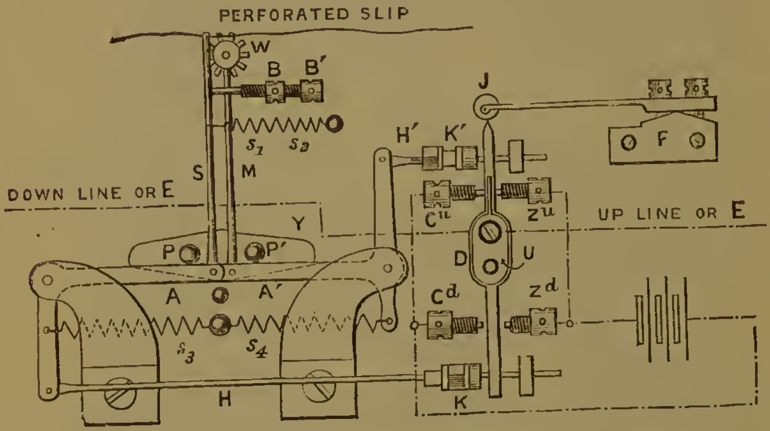


Fig. 288.—Diagram of the Wheatstone Automatic Transmitter.

the contact lever D, which is pivoted at U; this lever consists electrically of two parts insulated from one another and connected respectively to the two ends of the circuit into which currents have to be sent. One of these parts is the body of the lever, which, when rocked, comes into contact with one or other of the lower contact points C*d* or *Zd*. The other part is a little tongue placed at the top end of the lever so as to strike either of the contacts C*u* or *Zu*. Of these four contacts, two, C*d* and C*u*, are joined to the positive, and the other two, *Zd* and *Zu*, to the negative pole of the battery, as shown. When the lever D is rocked clockwise by the upward movement of M, its lower part is brought into contact with the positive pole C*d*, and its upper tongue into contact with the negative pole Z*u*; a current in a certain direction flows into the circuit of which these two parts form the terminals. On the other hand, when the lever is rocked counter-clockwise by the motion of S, it is easily seen that a current in the opposite direction flows into the same circuit. The former current is the "marking" current, causing—in a manner to be presently explained—a mark to be made on the ribbon of the receiver, whilst the latter is the reverse, or "spacing," current, during the continuance of which no marks appear at the distant end.

Referring now to the diagram of the punched slip, it will be seen that for a Morse "dot" the two holes on either side are opposite one another, and consequently a "marking" current is immediately followed by a "spacing" current, and the former has only time to write a "dot." But when the lower hole is displaced to the right of the upper one (as in the letter "T"), the "spacing," or reverse, current follows the marking current at a longer interval, and therefore a "dash" is written down. With this transmitter the high speed of 600 words per minute has been attained—a wonderful triumph when it is remembered that this is about four times as fast as an ordinary rapid speaker talks.

The Receiving Instruments.

As already remarked, these may be either non-recording instruments delivering an audible or a visual message, or they may be recording instruments, which write down or print the message in some convenient manner. In each class there are many varieties, and we select for description one from each which is most widely used in this country.

The Sounder and Bell.—Of all telegraphic receivers the simplest is the "Sounder." It consists of an ordinary two-limb electro-magnet arranged to attract a bar-armature.

When the armature is attracted, a piece of metal connected to it strikes against a stop, making an audible sound. On the cessation of the current the armature is pulled off by a spring, and the piece of metal strikes against another stop, giving a slightly different sound. An expert auditor, without looking at the instrument, can distinguish between these sounds and tell how long the current has been kept on. The briefest current signifies a "dot" on the Morse code, and a current kept on three times as long represents a "dash." The intervals between the signals of the same letter are equal to the time for a "dot"; between the letters of a word the interval is equal to three "dots," whilst between separate words it is five.

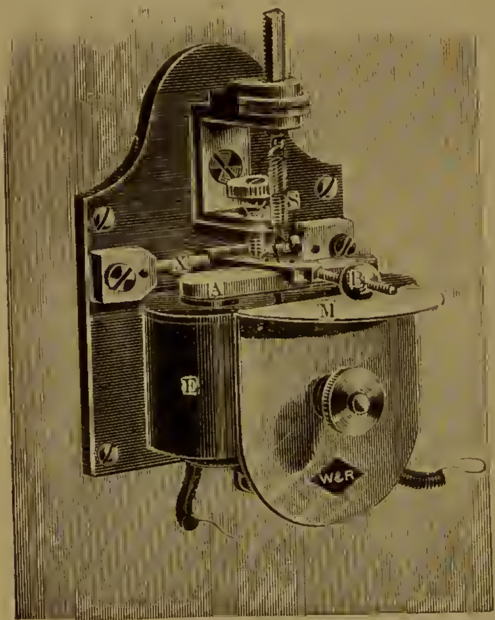


Fig. 289.—The "Bell" form of Sounder.

A modification of the "Sounder," known as the "Bell," is shown in Fig. 289. The electro-magnet E and its armature A can easily be distinguished. The latter can move about the pivoted axle X, with which it is connected by a cross-arm of brass, a prolongation of which carries the ball B. Underneath the latter is the metal plate M, free to vibrate, and so adjusted that B strikes it when the armature is attracted. The spring S, the tension of which can be adjusted, pulls the armature off when the current ceases. The signals are read in the manner just explained.

In some systems two "Bells" tuned to different notes are used. One of these is struck when a current in a certain direction is received, and the other on the reception of a reversed current. In this case the different tones of the bells represent respectively the dots and dashes of the Morse code.

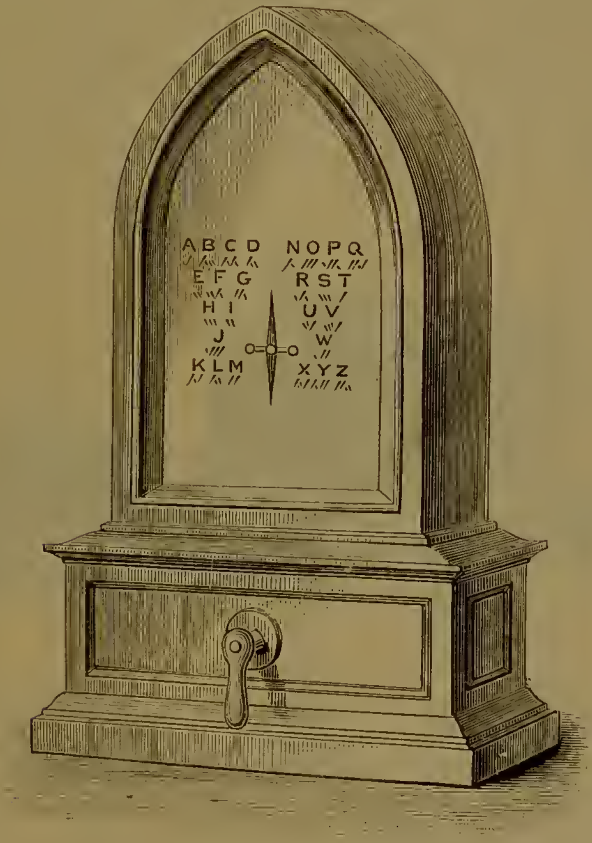


Fig. 290.—The Single-Needle Instrument.

The Single-Needle Instrument.—The instrument still most widely used for railway telegraphy is the "Single-Needle," which is simply a vertical galvanometer or galvanoscope having a gravity control. One form of it is shown in

Fig. 290. The magnetic system consists of a magnetic needle mounted on a horizontal axis and so weighted that it stands vertically when no current is passing through. On the same axis is the pointer seen in front of the dial, behind which the coils are hidden. The needle moves either clockwise or counter-clockwise, according to the direction of the current. A movement of the top end to the left is equivalent to a "dot," and a movement to the right to a "dash," on the Morse code. In railway work various special signals are used. The handle seen below the dial is connected to the transmitting part of the instrument, which is a reversing commutator. When the handle is moved to the left, a current is sent which deflects the needle counter-clockwise, but when it is moved to the right it causes a deflection in the opposite direction.

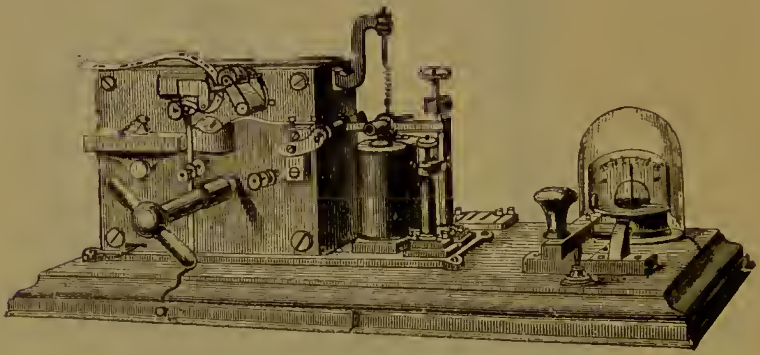


Fig. 291.—The Ink Writer.

The Morse Ink Writer.—Turning now to the recording instruments, we shall confine our remarks to the best known of these, the "Ink Writer." This instrument has some parts in common with the "Fast-Speed Transmitter" already described. Thus a strip of paper is drawn through the instrument by clockwork contained in the box on the left of Fig. 291. In this case, however, the paper is not perforated, but is drawn by the friction of rollers from a horizontal coil of paper contained in the drawer beneath. Against this band of paper as it passes over one of the rollers is pressed, whenever a current is received, the upper rim of a wheel whose lower part dips into an ink-well, which thus inks the rim. The inking roller *r* and the electro-magnetic arrangements are shown on an enlarged scale in Fig. 292. F is the armature of a two-limb electro-magnet

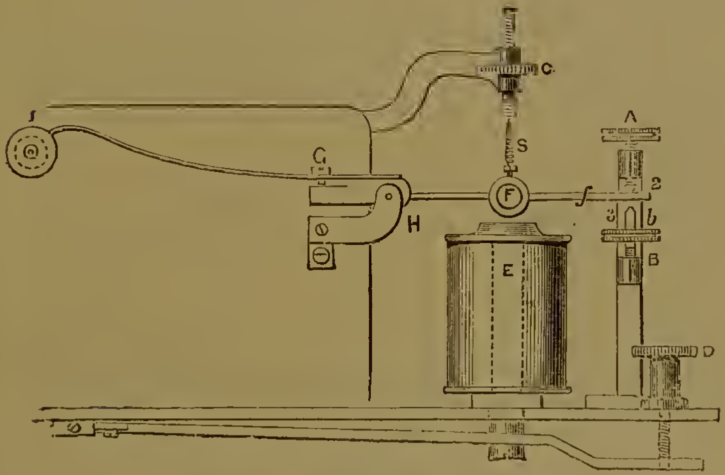
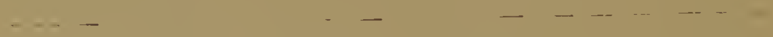


Fig. 292.—Details of the Ink Writer.

E, and is attached to one end of a lever which moves about H as a fulcrum. The other end of the lever carries the inking roller *r*, so that whenever F moves downwards by the attraction of the magnet, *r* moves upwards and comes into contact with the band of paper which is travelling above it. As long as the contact continues, *r* makes a mark on the paper; but as soon as the current ceases, the spring S pulls the armature F off the magnet, and moves *r* out of contact with the paper. Thus lines of any desired length can be made on the paper, and a message written according to the Morse code given on page 573. For instance, the word shown as perforated for the transmitter on page 579 would appear thus :—



The movements of the lever are limited by the projecting tongue *f* (Fig. 292) moving between adjustable stops. In Fig. 291 the lever on the right-hand is an ordinary Morse key for sending a message, and the little galvanometer at the back is to show that currents are actually passing.

The fast-speed receiver differs somewhat in its mechanical details from the instrument just described, but the principles used are the same, so that it is unnecessary to give a separate description of it.

Relays.—If the telegraphic stations be far apart, the connecting conductor necessarily has a high resistance When this is the case, increased battery-power is required to produce the currents necessary to work the instruments above described. Such an increase is expensive, and, moreover, leads to other troubles. A very ingenious way ot getting over the consequent difficulties is to use a piece of apparatus invented by Wheatstone, and called a "relay."

The relay is an electro-magnet wound with many turns of fine wire, so that a very feeble current will produce the requisite magnetomotive force. The armature of this electro-magnet is a very delicately pivoted lever or tongue, whose sole function is to open and close a local circuit electrically quite independent and separate from the line-circuit coming from the distant station. This circuit contains a battery and a receiving instrument, and is entirely contained within the receiving station. The tongue of the relay is made as light as possible, and the distance its end has to move over is sometimes as small as one-fiftieth of an inch. Thus a received current quite incapable of moving the heavy lever of an ink-writer, for instance, can draw over this light tongue and close the "local" circuit, causing the local battery to supply the current required to actuate the ink-writer. The long-distance fast-speed messages are always received in this way on beautifully delicate relays.

The Circuits.

Electrically, the instruments just described, as well as others designed for the purpose of transmitting and receiving telegraphic signals, may be connected to the batteries and the conducting circuits in various ways, each of which has some special advantages. Only some of the most widely used of these can, however, be described here.

The Single-Current System.—The simplest method of all, known as the "Single-Current Direct" system, is depicted in Fig. 293. Two stations—one on the left and one on the right—are connected by a single overhead wire L, technically referred to as the "line"; these stations may, of course, be many miles apart. M and *m* are the Morse keys, shown as resting on their back contacts P and *p* when not in use (*see* Fig. 284). These back contacts are connected to the earth-plates E E through the coils R*r* respectively of the electro magnets of the receiving instruments, which may be either "Sounders" or "Ink Writers." The middle contacts are both joined to "line," so that there is a complete conducting circuit through the "line," the receivers, and the earth; but as there is no battery in this circuit, no current flows. The batteries C Z and *c z* have their negative terminals Z and *z* also connected

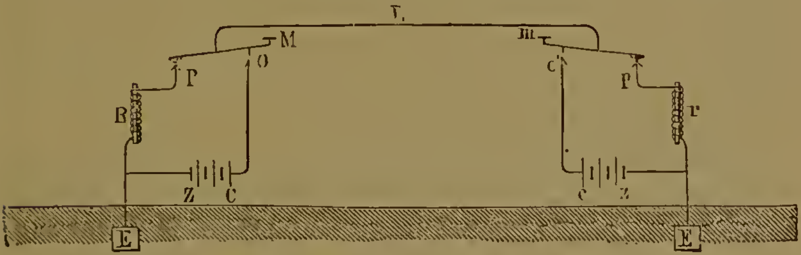


Fig. 293.—Connections for Single-Current Direct Working.

to the earth-plates, whilst their positive poles C and *c* are connected to the front contacts O and *o* of the Morse keys. If, now, M be depressed so as to break contact at P and make contact at O, a current flows through the circuit C, O, M, L, *p*, *r*, E, E, Z, energising the electro-magnet *r*, and giving the required signal at the distant station. This station, in its turn, by depressing the key *m*, can send a current from its battery through R, giving a signal at the other station. If both keys be depressed simultaneously, no signals are given or received.

This system, though so simple, is in practice only applicable to short lines or unimportant stations, where speed is not essential. High speeds cannot be obtained, because of the retardations of the rise and fall of the current due to self-induction, as explained in the previous section of this book. Further retardation is also caused by the electrostatic capacity of the line.

The Double-Current System.—In order to minimise the effects of induction, both electro-magnetic and electrostatic, a system is used in which, after every signal, a current in the reverse direction is sent round the circuit, so, as it were, to sweep out the effects of the last current, and prepare the line for the next signal. The key by which these changes are accomplished has already been described in detail (page 575), and also the way in which it is joined to the battery and the conducting circuit consisting of "line" and "earth." The connection of the receiving instrument to the screw M (Fig. 285) has also been explained, together with the use of the switch S. This key, connected up as described to battery, line, earth, and receiving instrument, simply takes the place of the Morse key, battery, and receiving instrument in Fig. 293. With the Double-Current system much greater speed can be attained than with the Single-Current system, an expert hand-signaller being able to send over forty words per minute.

In both the systems just described only a single message in either direction can be sent along the line L at any time. If these were the only systems available, a very heavy outlay on "lines" would be necessary in Great Britain, and sixpenny telegrams would be financially impossible. Fortunately, it is possible to so arrange the instruments that two, four, or more messages can be *simultaneously* sent along the same wire, thus greatly increasing its working value. The simplest of these is

The Duplex System.—The object aimed at in "duplexing," as it is called, a telegraph line is to so arrange the transmitting and receiving instruments at each end that messages can be simultaneously sent in both directions at the same time, thus doubling, as it were, the earning capacity of the line. There are two chief methods of doing this. One is to arrange the instruments at each end similarly to the circuits in a Wheatstone Bridge, as used for testing resistance. The other is to take advantage of the principle of the Differential Galvanometer. The latter is almost exclusively used in this country, and we shall therefore briefly indicate its chief features.

Reverting to our previous descriptions of "Galvanometers for measuring small currents," it is obvious that if, instead of winding the conducting circuit with a single wire, we were to wind it with two exactly similar wires lying alongside one another throughout their length, then each of these wires could be used independently to measure a current. Moreover, if the two wires have been carefully wound, the same current passed through either of them indifferently will produce the same deflection of the needle. If, therefore, currents be passed through the two coils *in opposite directions*, the needle will only be deflected if these currents are *unequal*, and will *not be deflected* at all if they are *exactly equal*. Moreover, any deflection of the needle will depend on the *difference* of the two currents; hence the instrument is called a "**Differential Galvanometer.**"

The same principle may be applied to any electro-magnetic instrument, such as the electro-magnets of a relay.

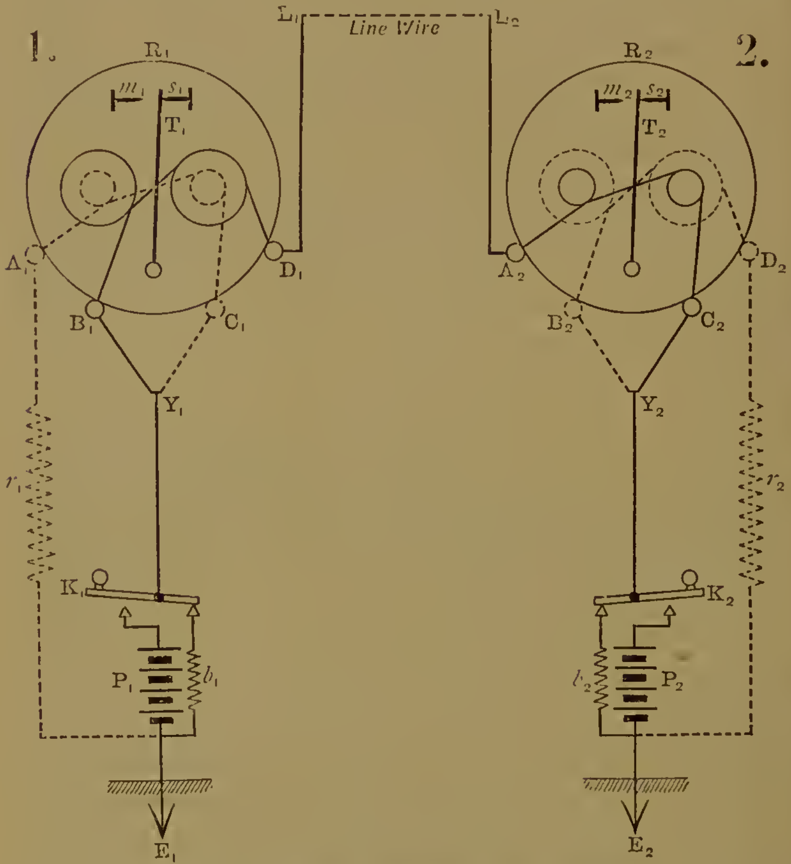


Fig. 294.—Diagram of Differential Duplex Telegraph.

That is, the conducting circuit may be wound in two parts in such a way that, when oppositely-directed currents are sent through these, the magnetic effect produced will depend on the difference of these currents, and will, therefore, be *nil* when the *currents are equal.*

The existence of such instruments makes differential duplex working possible, and in Fig. 294 we give a diagram of the arrangements at two stations **1** and **2** connected by a line wire $L_1 L_2$. The arrangements shown are those for duplexing a single-current system. The two equal batteries P_1 and P_2 are connected to the Morse keys K_1 K_2 as shown, the earth connections to the back contacts being through resistances b_1 b_2, approximately equal to the resistances of the respective batteries. R_1 and R_2 are two similar relays "differentially" wound, the two circuits in each case being, for clearness, indicated, one by a continuous, and the other by a dotted line. In series with the dotted circuits are the resistances r_1 r_2, known as the "compensating" resistances. If the oppositely-directed currents in these two circuits are equal, the tongues T of the relays are unaffected; but if they are unequal, they are moved against either the stops m or the stops s. Whenever either tongue strikes against the corresponding stop m it closes a "local" circuit containing a battery and the receiving instrument, and thus gives rise to a signal on the latter.

Suppose, now, that the key K_1 is depressed. A current generated by the battery P_1 flows through the key to the point Y_1, where it divides into two parts. One portion flows through the circuit B_1 D_1 of the relay R_1, the line L_1 L_2, the circuit A_2 C_2 of the relay R_2 to Y_2, the back contact of K_2 through b_2 to earth, and so back to the battery. The other portion of the current flows through the coil C_1 A_1 of the relay, and the resistance r_1, back to the battery. Now, if the resistances of these two paths be exactly equal, the currents in them will be exactly equal, since the same P.D. is used to produce both currents. In this case, therefore, the tongue T_1 of the relay R_1 is unaffected, and causes no signal at station **1**. But the relay R_2 at station **2** has a current passing only through one set A_2 C_2 of its coils. The tongue T_2 attached to its armature is, therefore, moved so as to come against the contact m_2, thus causing a signal on the receiving instrument. In this way the desired signal is made at station **2**. In the same manner, when key K_2 is depressed, a signal is given at station **1**, and none at **2**.

The condition for the equality of the currents in the relay R_1 just referred to evidently is that the resistance r_1 of the dotted path from A_1 to the battery should equal the resistance of the other path from D_1 through the distant station to earth and battery.

We must still inquire what happens when both keys K_1 and K_2 are depressed simultaneously—that is, when both operators desire to send signals at the same time. In this case the points Y_1 and Y_2 are both brought to the same potential, and no current can therefore flow along the conductor, $Y_1 B_1 D_1 L_1 L_2 A_2 C_2 Y_2$ joining them. But a current *can* flow through the compensating circuit $Y_1 C_1 A_1 r_1$ and back to the battery P, and another current *can* flow through the circuit $Y_2 B_2 D_2 r_2$ back to the battery P_2. Thus both the relays R_1 and R_2 have currents flowing in one coil only, and therefore, since these currents are in the proper direction for the purpose, the tongues T_1 and T_2 will be moved against the "marking" contacts m_1 and m_2 respectively. Signals will, therefore, be recorded at both stations as desired. The curious feature of this last case is that, although both stations receive signals because of the actions at the distant stations, *no current passes along the line* $L_1 L_2$.

In actual practice differential galvanometers, as well as differential relays, are in circuit at both stations to facilitate adjustments and for other reasons. The application of duplex working to the double-current system is substantially the same in principle as that just described, but a little more complicated in practice. For all long-distance work the double current is used, because of the increased speed, due to the actions already explained.

Quadruplex Working.—A further development of duplex working is that in which *two* messages can be sent simultaneously *in each direction*, making four messages in all, thus giving rise to "quadruplex" working. This is accomplished by using two different kinds of currents for signalling. In one class the two signals required by the Morse code are produced by currents in opposite directions; in the other class the two distinctive signals are given by weak and strong currents irrespective of direction. Special sending-keys are, of course, required for each class of signals, and also special receiving relays. The latter must be such that one relay responds only to signals of the first kind, whilst the other responds only to signals of the second kind. The description of these instruments would, we fear, lead us too far into technical details.

Multiplex Working.—There is still another way of increasing the number of messages that can be sent simultaneously on one wire. The method is known as "multiplex," and depends for success on the absolute synchronism with which two revolving commutators at the two ends of the line can be kept "in step." When this is accomplished, the commutators put each pair of correspondents on to the line for a fraction of a second and then connect up the other pairs in order, returning finally to the first pair in less than a second to repeat the cycle of connections over and over again. Between London and Birmingham as many as six pairs of correspondents are thus enabled to send messages at the same time on one wire.

Printing Telegraphs.

Besides the instruments already described, which use the Morse code with its two distinctive signals, there are others which print off the messages in ordinary type. Of these, the ingenious transmitters and receivers devised by Professor D. E. Hughes are much used on the Continent. But instead of describing these, which are seldom seen

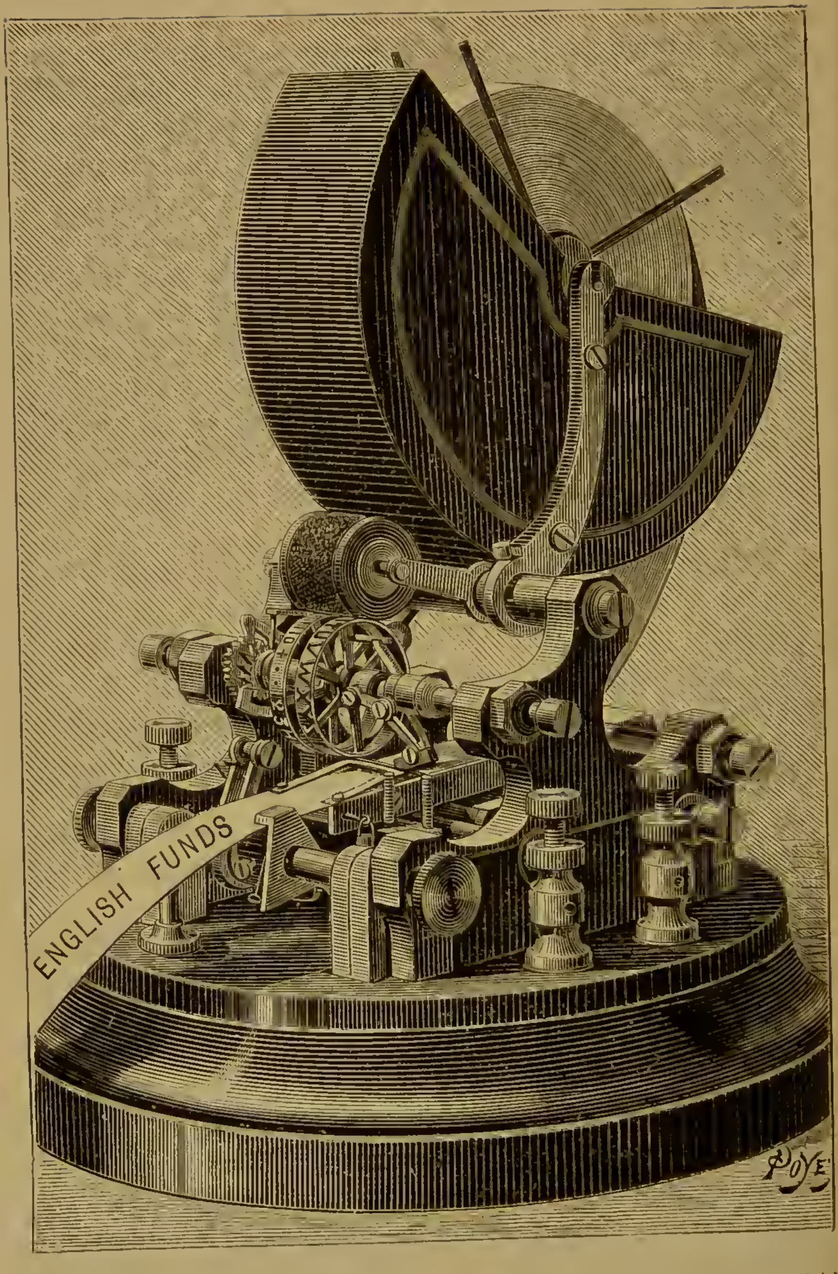


FIG. 295.—THE RECEIVER OF THE "TAPE" PRINTING TELEGRAPH.

in England, we propose instead to devote a little of our limited space to the very similar instruments which are used for the purpose of disseminating news to subscribers from a central news office.

Of these, the most familiar to the general public is the receiving instrument depicted in Fig. 295, which in busy mercantile centres, under the name of the "tape," has long since become a necessity to the pushing business man of the nineteenth century. In clubs and hotels, also, the little glass-encased instrument, quietly feeding its yards of the latest news into a basket at its side, has become a familiar figure. But, although the message is printed in ordinary letters, so that it is not necessary to learn a new alphabet in order to decipher it, still there is, as it were, a residual amount of inconvenience in having to pass the long paper tape more or less slowly through the fingers whilst reading. Moreover, it will sometimes happen that many yards of paper have to be passed before the particular message sought is found. This last inconvenience is partly overcome by cutting the tape at intervals and pinning it on a notice-board: at the best, however, this device, it must be confessed, is somewhat lame. Hence the attention of inventors has been directed to perfecting instruments that shall be capable of printing the message in "column" form, as is done by the ordinary type-writing machine.

In the "Tape" machine (Fig. 295) we may explain in general terms that the type-wheel, which can be plainly seen in the figure, is revolved until the desired letter is opposite the tape, when the wheel is stopped and the tape moved against it, thus receiving an impression of the letter from the inked wheel. How these movements are controlled electrically we shall explain when we describe the transmitter.

The Column Printer.—The additional movements to be provided for in a column instrument are sufficiently obvious. Assuming that the paper is fed forward at proper intervals, the type-wheel must be made to traverse the paper sideways from left to right, with a step-by-step movement which advances it through the breadth of one letter between each impression on the paper. The spaces between successive words can be provided for by a blank on the type-wheel. In addition to this lateral movement there must be an arrangement for bringing back the type-wheel to the left-hand side when it has traversed the whole breadth of the paper, and simultaneously the paper itself must be fed forward by a space equal to the distance between two successive lines. Finally, the receiver should be so well adapted for the work that it can receive the messages without danger of confusion as rapidly as an expert telegraph operator can transmit them.

Before the action of the "printer" itself can be readily followed, we must describe the "transmitter," which is confined to the privacy of the Central News office. This instrument is shown in Fig. 296. It is provided with a key-board fitted with long white and short black keys alternately. Each key corresponds to a particular letter or signal, and corresponding letters are arranged in the same order round the type-wheel in the printer. Over the back ends of the levers, of which the keys form the front ends, there revolves a cylinder carrying a set of projections helically arranged, so that each is brought successively in a vertical position over one of the levers. Synchronously with the revolution of this cylinder a series of interrupted currents are sent into the circuits of the receiving instruments, and these cause the type-wheels of the latter to revolve at a speed exactly equal to that of the cylinder in a manner to be described presently. As long as no keys are depressed, the cylinder and the type-wheels rotate uninterruptedly; but when a key is depressed, then, as soon as the corresponding projection on the cylinder in its rotation comes opposite to it, it is caught by the lever at the back

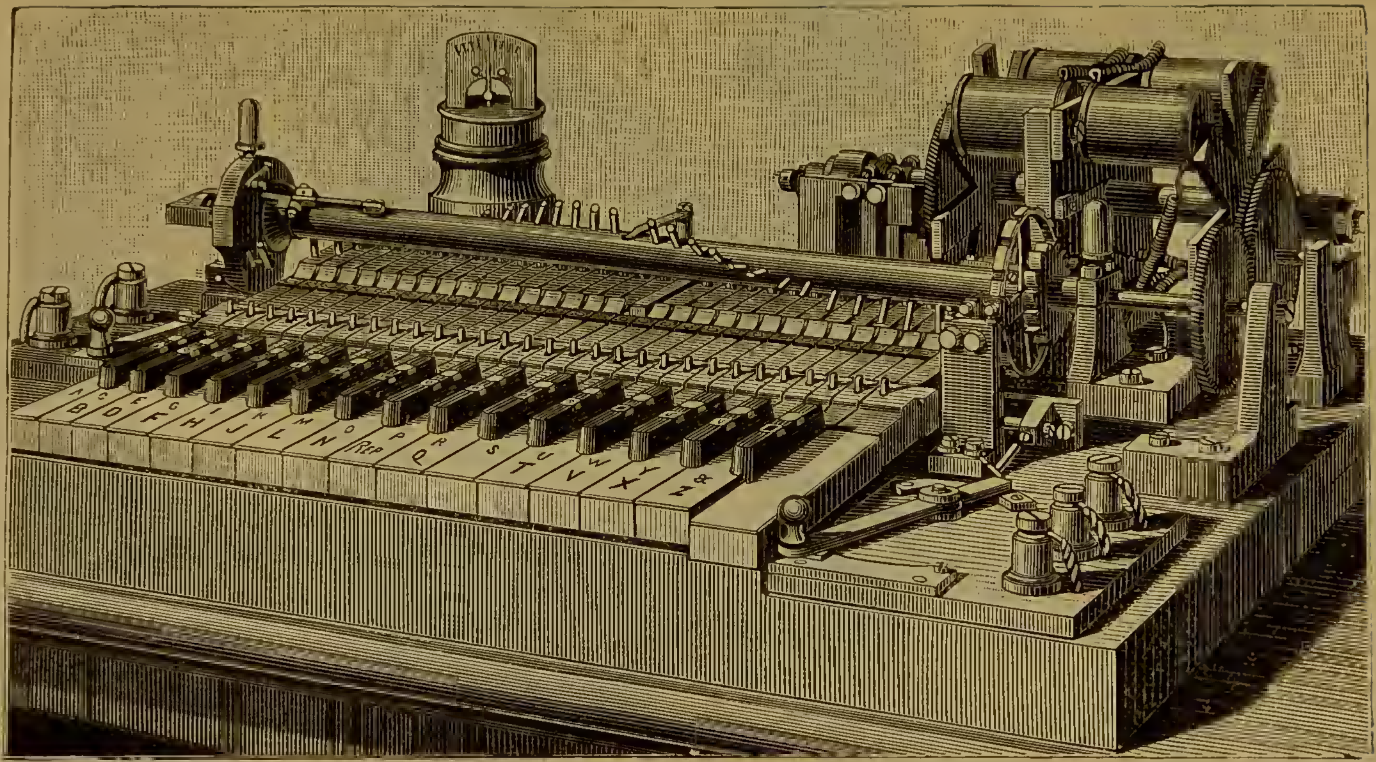


FIG 296.—THE EXCHANGE TELEGRAPH COMPANY'S TRANSMITTER.

and the cylinder is stopped, simultaneously stopping the currents above-mentioned, and, therefore, stopping the type-wheels. At the same time another circuit is closed by the projecting spur, which transmits another current to the

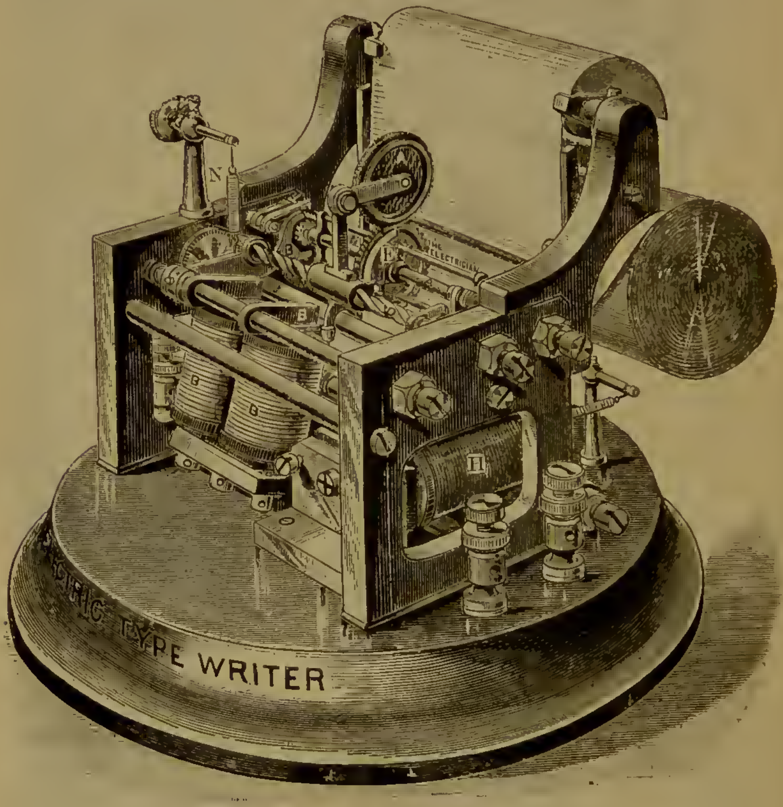


Fig. 297.—Higgins' Column Printer.

receivers and causes the mechanism for printing to come into play.

In passing, we may remark the receivers are not worked directly by the currents from the transmitters, but that relays are interposed, which render control easier, and also make it possible to work more circuits with the one transmitter, each circuit being actuated by one relay, and a number of relays being put in series. In this way as many as eighteen hundred receivers can be served by a single transmitter.

Turning now to the receiver, we shall describe the "Column" printing instrument invented by Mr. Higgins, of the Exchange Telegraph Company. We select this because it was the first column printer developed to the stage of being practically successful in actual working, and, moreover, is adapted to the transmitter just described. The instrument is shown in perspective in Fig. 297, and an outline plan of it is given in Fig. 298. The broad band of paper required for the printing is contained on a roller at the back, and the part receiving the message is held firmly in appropriate grips during the printing of a line, but can be fed forward when required. E is the type-wheel sliding on the axle D and the two eccentric rods D′D′; these rods and the axle are moved round step by step by the action of the pawl C² and the ratchet-wheel *c*′. The arm of this pawl is

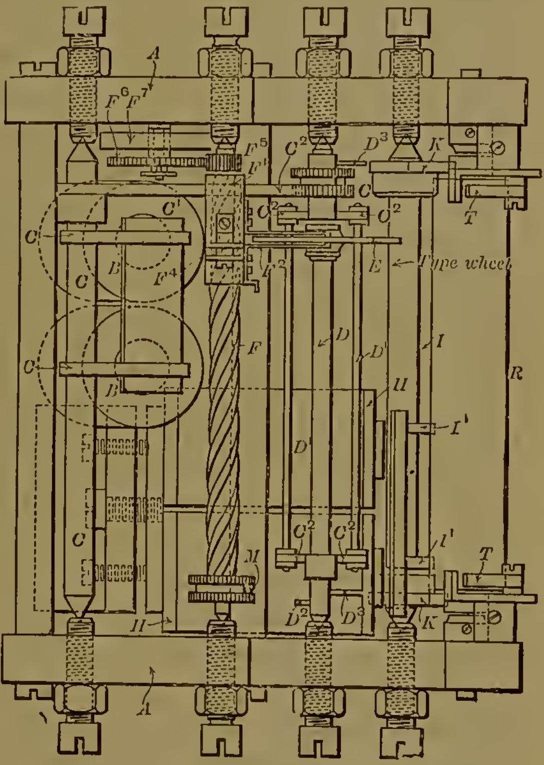


Fig. 298.—Plan of Higgins' Column Printer.

attached to the rocking-axle C, which in its turn is connected by the arms *c* to the armature of the electro-magnet B. This magnet receives the rapidly interrupted currents from the transmitting instrument; whenever a current passes, the armature is drawn down, but is drawn back again by the spring N (Fig. 297) when the current is interrupted. Thus the type-wheel is caused to revolve synchronously with the currents sent from the transmitter. When the currents are stopped by the depression of one of the lettered keys of the transmitter, the type-wheel stops with the corresponding letter opposite the paper. At this moment, as already explained, a second or printing circuit is closed at the transmitter, and a current passes through the printing magnet H; the armature of this magnet is attracted, and, by means of the arms I′I′ attached to a rocking shaft I, moves forward the frame carrying the paper; thus the latter is brought in contact with the type-wheel and receives the desired impression. As this framework falls back it brings into play the mechanism by which the type-wheel is moved laterally through the space of one letter. On referring to Fig. 298 it will be noticed that the type-wheel and inking roller are connected to a sleeve or nut travelling on the quick-threaded screw F; if the latter be turned, the type-wheel, etc., must be moved sideways either to the right or left. Now as the paper frame falls back it moves a lever and pawl (not shown in Fig. 298) which act on the ratchet-wheel M, and turn the screw F just sufficiently to move the nut F′ one space to the right. At the same time the toothed wheels F^5 and F^6 are moved round, and a watch-spring in F^7 is partly wound up. This coiled spring is used to return the type-wheel, etc., back to the left-hand side when it has completed a line. To do this a special key has to be depressed in the transmitter, which causes the type-wheel shaft D to stop in such a position that, when the paper-carrying frame falls back after advancing only a part of the usual distance, a pin D^2 on D acts upon a system of levers which lifts the ratchet off M and thus releases the shaft F. The coiled spring then rapidly rotates this shaft in the backward direction, and thus brings the type-wheel quickly to the beginning of a fresh line. At the same time the pin D^2 acts upon another system of levers which, as the paper-carrying frame moves towards the type-wheel, causes the paper to be fed forward through a space equal to the distance between two lines. In order to place a proper space between separate messages, or to bring forward the paper so as to expose the end of the last message printed, it is only necessary to depress the special key on the transmitter several times in succession, and at each depression the paper will be fed forward through the above-named distance without anything being printed on it.

With the description of these ingenious instruments we must bring our remarks on overland telegraphy to a close. We must not, however, leave the general subject without devoting some little space to the still further wonderful triumphs of engineering and scientific skill involved in submarine telegraphy.

SUBMARINE TELEGRAPHY.

When it is attempted to apply the methods and systems already described for the purpose of communicating between countries separated by seas or oceans, numerous additional difficulties present themselves, of such a nature as to greatly modify the details of the apparatus employed. Besides, there is the initial difficulty—which delayed the development for many years—of establishing a conducting communication between the two countries concerned. It is no longer a case of wires stretched on posts through the non-conducting air, but of passing a properly insulated conductor through a good conducting medium, and that a medium in which it is impossible for men to live and move freely. However deep the ocean, the work of placing the conductor or cable must be carried on from the surface, and many mechanical difficulties have to be overcome. Moreover, as regards the insulated conductor, several trials and failures were made before a sufficiently good form for permanent work was evolved.

Before proceeding to describe some of the chief instruments used in submarine telegraphy, a brief historical sketch of the early struggles and difficulties of cable-laying may not be without interest to our readers.

Historical.—It has been already mentioned that Le Sage in 1774 and Salva in 1795 proposed the use of insulated cables for electric circuits. In 1812 Schilling laid such cables in the Neva, and by their means exploded powder mines. In 1839 Sir William O'Shaughnessy Brooke, in some telegraphic experiments in Bengal, used a circuit 21 miles long, 7,000 feet of which consisted of a cable sunk in a river; and to him, therefore, belongs the credit of first actually transmitting signals under water. For insulation he used pitch and tarred hemp. A similar experiment was made by Ezra Cornell in the River Hudson in 1845, between Fort Lee and New York, a distance of 12 miles. He used a double-wire cable, with indiarubber insulation in a leaden tube; but after some months his cable was cut by the ice. Meanwhile several proposals had been made for connecting France and England and Europe and America.

The first cable between France and England was laid in August, 1850: it consisted of gutta-percha-covered copper wires sunk by leaden weights attached to it at intervals. It was broken -it is supposed by friction against the rocks—before the laying was completed. The following year a better designed cable was laid; the gutta-percha-covered wires, of which there were four, were protected with tarred hemp and cord, and outside these ten strong iron wires were wound. This cable was the first used for public messages, and, though frequently repaired, has never been entirely renewed. Its success led to the laying of numerous short cables in different parts of Europe.

The more serious problem of laying a cable from Europe to America was now hopefully attacked. Tibbets and Gisborne formed the Electric Telegraph Company of Newfoundland in 1851, and connected Cape Breton with Nova Scotia. In 1854 this company was merged into a larger company formed by C. W. Field, and a cable 85 miles long was successfully laid between Cape Breton and Newfoundland. Field then visited England and, in conjunction with Sir Charles Bright, Sir John Pender, and others, formed the Atlantic Telegraph Company, with the object of laying a cable across the Atlantic Ocean. The kind of cable decided upon is shown in Fig. 299. It consisted of seven copper wires *a*, each 0·03 inch diameter, which were covered with three layers *b* of gutta percha; outside these there was a covering *c* of jute, and finally, to strengthen the cable and protect it from being cut through by rocks, eighteen iron ropes *d*, each made of seven iron wires, were wound on. This was the deep-sea portion; the shore end was still more heavily armoured with iron ropes. The cable was placed on board two Government vessels—the English ship *Agamemnon* and the United States ship *Niagara;* and the laying-down was commenced on August 7th, 1857, from Valentia, in Ireland, along a route previously surveyed by

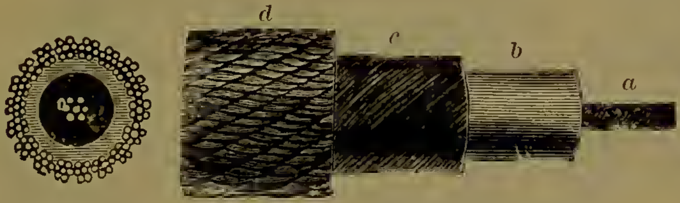


Fig. 299.—The First Atlantic Cable.

Captain Maury. On the third day, after 334 knots had been paid out, the cable broke at a place where the ocean was more than two miles deep. The ships then returned to England, and more cable having been manufactured to replace the lost portion, and better paying-out machinery having been constructed, another attempt was made in 1858. This time the laying down was commenced in mid-ocean, the two vessels steaming—one towards Valentia and the other towards Newfoundland. After several mishaps the cable was successfully laid, and the first message transmitted on the 7th of August, 1858. The insulation of this cable, however, was not very good, and rapidly became worse, until, on the 1st of September, it broke down altogether.

In the next attempt, in 1865, a much better designed cable was used, and the largest vessel then afloat, the *Great Eastern*, was chartered to lay it. Several mishaps occurred during the laying; and eventually, when within 600 miles of Newfoundland, it broke, and all attempts to grapple the broken end were unsuccessful.

With all the experience now acquired, another attempt was made in 1866, and this time the *Great Eastern* successfully accomplished the task in fourteen days, the end of the cable being finally landed on the 27th July, and the line being opened for public messages on the 4th August following. The length from shore to shore was about 2,140 miles.

Since that date many other cables, with an aggregate length of over 164,600 miles, have been laid in all parts of the world; and the Atlantic itself is now spanned by no fewer than twelve cables connecting Europe with North America. For the work of cable laying and repairing, a special fleet of steamers has been built, and is being continually added to; so that what was accomplished with so much difficulty and risk as late as 1866 is now a matter of ordinary commercial practice. At the present moment the project of connecting our Australasian Colonies to the west coast of Canada by a cable across the Pacific is being seriously advocated. If laid, this cable will be in all about 6,700 miles long, but will be laid in sections, touching at some of the Pacific islands *en route.*

Modern Submarine Telegraphy.—The difficulties which limit the speed of signalling on long land-lines, owing to the effects of electrostatic induction, are much more severely felt in cable work. The conductor of a land-line is usually many feet from the surface of the conducting earth, whereas the insulated conductor of a submarine cable is very close to, and is entirely surrounded by, the conducting sea-water. The electrostatic strains set up in the dielectric in the latter case, when the conductor is brought to a potential different from that of the water, are much greater than in the former case, and the disturbing effects are correspondingly increased.

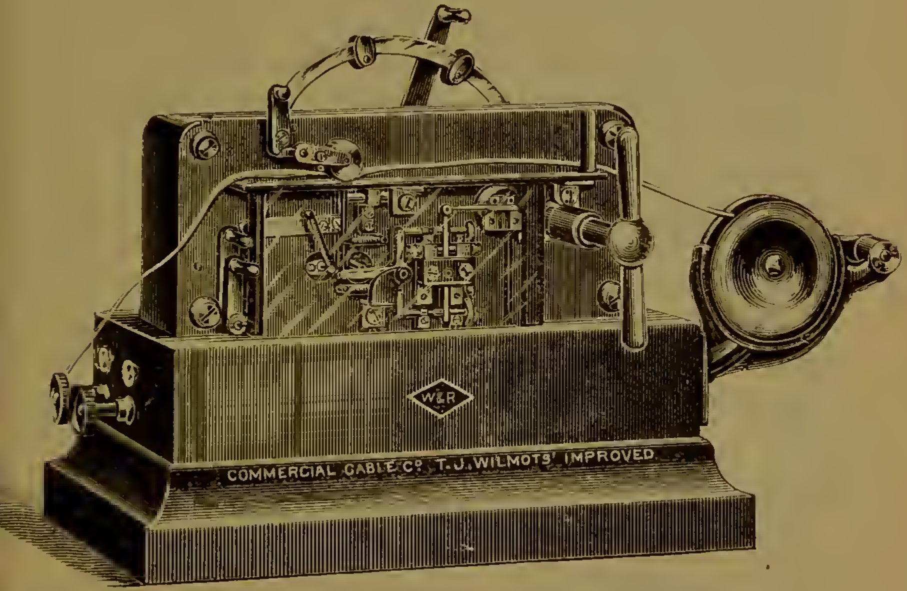

W&R
COMMERCIAL CABLE Co T. J. WILMOTS' IMPROVED

Fig. 300.—Wilmot's Automatic Transmitter for Cable-Work.

Many attempts have been made to minimise the disturbance by using special forms of keys and otherwise, but the speed attained for many years was very slow as compared with that on land-lines. Most of these earlier efforts used hand-signalling, and it was not till 1886 that a mechanical transmitter for ordinary signals was successfully applied to Atlantic work by Mr. T. J. Wilmot, the Superintendent of the Commercial Cable Company, at their landing station at Waterville, Ireland. Mr. Wilmot's transmitter is a modified and improved form of the automatic Wheatstone transmitter, already described (page 580). It is shown in Fig. 300, and in appearance much resembles the older instrument. The chief difference is in the system of levers and cams, by which the motion is transmitted from the perforated paper to the contact points. Also for cable work the dots and dashes of the ordinary ink-writer are not used, but, instead, we have the right- and left-hand movements of a recording galvanoscope produced by currents in opposite directions. The transmitter has to alter the contacts of the circuit to produce these currents, and the slip used is therefore punched differently. For instance, the specimen-word given on page 579, if intended for use with a cable transmitter, would appear thus on the strip :—

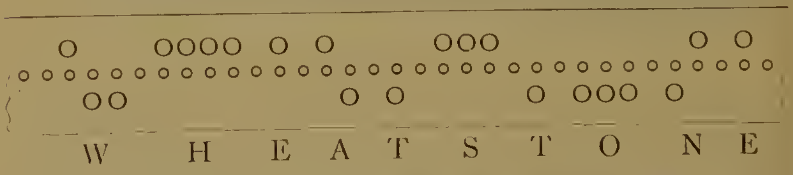


Fig. 301. Strip perforated for Cable Transmission.

Without going further into the differences between the two transmitters, we may say that a speed of 250 to 300 letters per minute is regularly maintained on the Atlantic cables with Mr. Wilmot's modified Wheatstone, and that the signals received are much more easily read than those produced by the slower hand-signalling.

The Siphon Recorder.—In the early days of cable telegraphy, delicate mirror galvanometers, such as we have described in a previous section, were used as receivers, and the movements of the spot of light to the right and left corresponded to the two distinctive signals of the Morse code. The reading of such a receiver was very fatiguing; the spot of light had to be constantly watched, for there was no sound like the click of the needle instrument to tell when a message was being commenced. Moreover, no record of the message was left, and the possibility of errors was much increased.

These receivers, therefore, wonderful triumphs of skill though they were, have now been completely superseded by another class of instruments, known as "Siphon Recorders." Originally devised by the same fertile inventor, Lord Kelvin, to whom we owe the sensitive mirror galvanometer, they have been successively improved by him and by others, until we now possess a receiver admirably adapted to the requirements of long-distance ocean telegraphy.

The Siphon Recorder is a sensitive galvanometer with the mirror removed, and its place taken by a siphon, from which ink can be spurted on to a ribbon of paper drawn past its end. The particular kind of galvanometer used is that which we have already described at page 353, under the name of the D'Arsonval galvanometer, the latter being, in fact, a siphon recorder adapted for ordinary laboratory work. A reference to our previous description will show that the essential part of this instrument is a light coil of conducting wire, which is free to move in a strong magnetic field, the movements being controlled by torsion. But instead of the deflections of the coil being indicated by a mirror reflecting a beam of light, a fine glass tube, about one-hundredth of an inch in diameter, is employed. This tube is bent into the form of a "siphon" (whence the name of the instrument), the short arm of which dips into an ink-well above the level of the paper. The movement of the ink in the tube is assisted by mechanical vibration, with the result that a shower of fine drops issues from the lower end on to the travelling paper ribbon. As this lower end is moved to the right and left by the movements of the coil, a wavy line is traced on the paper, giving the signals of the Morse code. Thus the word given above, as punched for the transmitter, would appear on the ribbon of the receiver thus:—

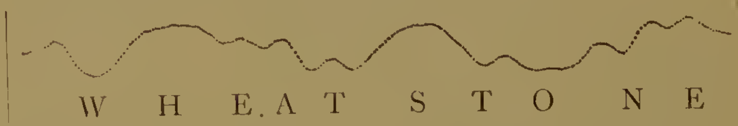


Fig. 302.—Message as written by the Siphon Recorder.

Both the punched strip and the received message are full size. One of the most modern forms of the siphon recorder, as improved by Mr. Charles Cuttriss, is shown in Fig. 303. MMM are horizontal circular steel magnets, which produce the field in the annular space in which the coil R swings; the latter is pivoted top and bottom in agate bearings, and carries eccentrically a piece of aluminium E with a slot at its upper end, through which passes one of the regulating fibres D′, by which the motion of the coil is transmitted to the siphon. At one end D′ is attached to a rigid support O, and at the other to a flexible spring F, adjustable by moving the index G′. This fibre and spring also furnish the force controlling the movements of the coil. Close to E the fibre D′ is crossed at right-angles by another fibre D, one end of which is attached to the adjustable spring F, and the other end to a projection from a vertical wire stretched in the tube L. To this vertical wire is securely fastened the siphon P, one end of which dips into the ink-well Q, and the other is close to the travelling paper ribbon J, on which a continuous stream of fine drops of ink is spurted. The movements of R, by means of the connections described, cause the end of P to travel to one side or other of the paper, thus converting what would otherwise be a straight line of dots into a wavy line.

The arrangements for causing the ink to flow through the siphon are particularly ingenious and distinctive of this form of the instrument. The table T, over which the paper ribbon passes, is the end of an electro-magnet, which is rapidly magnetised and demagnetised by means of an interrupted current supplied to it from a separate battery. Attached to the writing point of the siphon P is a little bit of No. 30 soft iron wire, about one-eighth of an inch long, and 0·012 inch in diameter, which is attracted every time the magnet T is energised, and springs back again on demagnetisation, thus setting the siphon in vibration and knocking the ink out of it. The interruptions of the current which

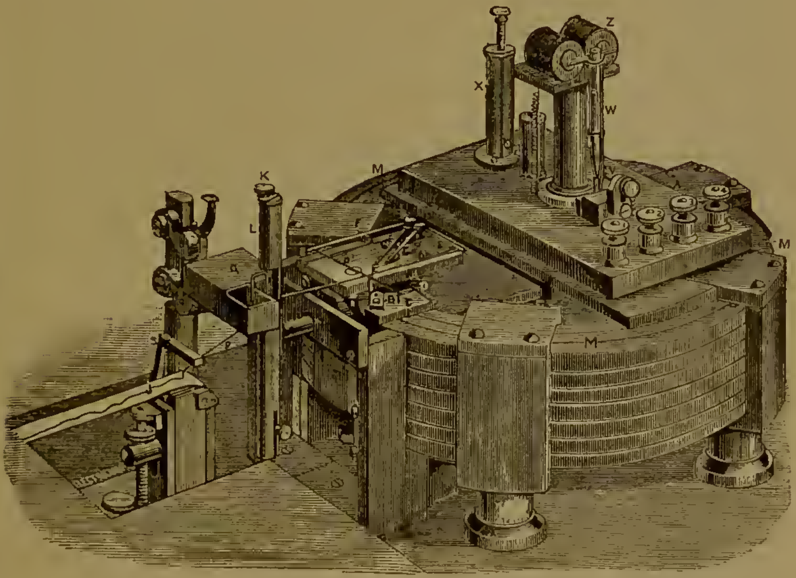


Fig. 303.—Kelvin's Siphon Recorder, Cuttriss' Form.

magnetise T are caused by the vibrator magnet Z, whose armature, being attracted, causes a break in the circuit at V, which acts like the break-contact of an electric trembling bell. Thus, when the armature is attracted, the current in Z and T is broken, the armature flies off again, remaking the contact at V, is again attracted, and so on. The rate of vibration of the armature, and therefore of the interruptions of the current, is regulated by the quantity of the mercury in the glass tube W attached to the armature. This tube is connected by a flexible tube to a reservoir X, containing mercury; in this reservoir is a plunger, which, when moved up or down, alters the level of the mercury in W, thus altering the moment of inertia and time of swing of the vibrating armature. The rate of vibration of W must be adjusted to correspond with the natural period of vibration of the siphon P, for it is only when the impulses are timed to agree with this period that the required effect is produced. By altering the mercury in W the rate can be varied between 60 and 100 impulses per second.

The Telephone.

Wonderful as are the results attained by the telegraph, it must be admitted that the achievements of the telephone are still more wonderful. For though communicating by preconcerted signals over a distance of thousands of miles is an exploit which in the no very distant past would have been pronounced absolutely impossible, the reproduction of spoken words marks a further advance not less surprising, and, at first sight, incredible. If, then, the history of the development of the former is comprised within the brief space of the last one hundred and fifty years, it is not remarkable that the record of the latter commences still later, and covers a period of less than forty years.

The difficulties to be surmounted can only be appreciated by a careful study of that part of the science of acoustics which treats of the forms of the waves by which speech is transmitted through the air from a talker to his auditor. These waves are exceedingly complicated. Neglecting for a moment the difference in the method of propagation, a slight idea of the complicated nature of the waves may be obtained by observing the waves of the ocean during a heavy storm. There are, first, the heavy rollers, with an interval of hundreds of feet from crest to crest; but between the two crests of successive rollers there is a series of numerous waves whose size is by no means contemptible. On these large waves are superimposed again still smaller waves, whose surfaces in their turn are furrowed by ripples, and even the ripples have still smaller corrugations disturbing the smoothness and regularity of their forms. Endeavour to fix the attention on a single particle of the surface-water, and consider for a moment how complicated its motion must be under the influence of all these waves. Then pass to the case of the sound-transmitting air, and realise, if possible, that the motions of any individual particle of air when transmitting speech, are much more complicated than those of the particles of water in the previous case, and much more rapid, inasmuch as some of the smaller ripples consist of vibrations of which hundreds take place in a single second of time. The difficulty of the problem to be solved will now, we hope, be somewhat apparent. The voice of the speaker sets up these complicated disturbances in the air immediately surrounding him. These disturbances have, then, to be reproduced in their entirety, wave for wave and ripple for ripple, down to the minutest peculiarity, at the distant place, in order that the listener may recognise not only the words spoken, but also the intonations and inflections of the voice of the speaker. That the reproduction is not altogether perfect, as yet, under all circumstances is not to be wondered at; the wonder rather is that any recognisable sound should have been reproduced at all.

Historical.—The idea of transmitting sounds to a distance along a stretched wire or string—as in the so-called "lovers' telephone"—is very old; but these transmissions were purely mechanical, and, from their nature, limited to short distances. It is not necessary, therefore, to consider them in detail.

The first discovery in the direction of the possibility of electrical transmission of sound was made in 1837 by Page, who observed that sounds were emitted by an iron bar when being magnetised. Joule afterwards showed that these sounds were accompanied by a very small but measurable extension of the bar in the direction of magnetisation, and were, therefore, due to sudden molecular movements. Attempts were made from time to time to utilise this discovery of Page's telephonically, but none were successful until 1861, when Philip Reis, a German schoolmaster, solved the problem, and actually transmitted musical sounds electrically to a distance. Indeed, there is very little doubt but that Reis also transmitted articulate speech. His transmitter consisted of an instrument with a loose contact, whose action will be better understood after we have described some modern transmitters. His receiver, however, was based on Page's discovery, and consisted of a knitting-needle surrounded by a simple solenoid and mounted on a resonance-box; and it was on the molecular sounds of the magnetisations and demagnetisations set up by the fluctuating currents in the coils that he depended for the reproduction of the distant sounds. Unfortunately Reis' discoveries were not brought prominently before the scientific world at the time, with the result that fifteen years later (in 1876) Graham Bell and Elisha Gray, each working independently and without knowledge of Reis' work, produced the practical solutions of the problem which form the starting-point of modern telephony. By a strange coincidence both these inventors applied to the United States Patent Office for their patents on the same curiously significant day—viz., St. Valentine's Day, February 14th, 1876. This brings us to the era of modern telephony, of which we shall now give a brief account.

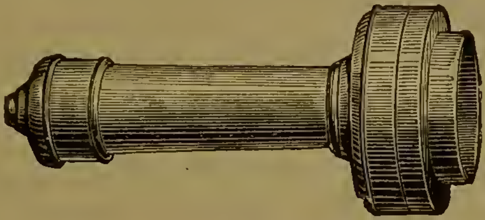


Fig. 304.—The Early Bell Telephone.

Modern Telephony.—In this subject we propose to follow the same plan that was employed in treating of modern telegraphy, and to describe separately the transmitters, the receivers, and the circuits and accessories. We shall, however, alter the order somewhat, and describe the receivers before the transmitters, for the curious reason that Bell's early telephones and most modern receivers can also be used as transmitters, though transmitters of a different kind, which cannot act as receivers, are preferable.

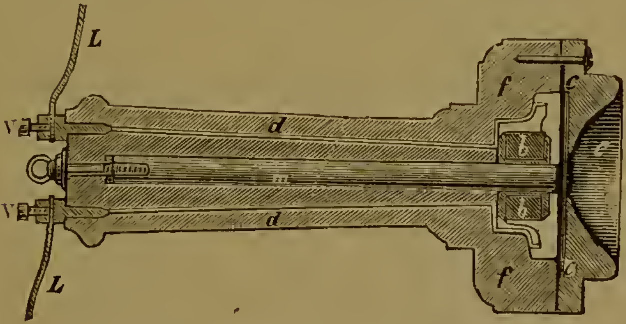


Fig. 305.—Section of the Bell Telephone.

Telephonic Receivers.—*The Bell Telephone.*—Without lingering over the details of the successive steps by which Mr. Graham Bell evolved the telephone, most interesting though those steps are, we shall at once describe the very complete instrument patented in 1876.

The outside appearance of this instrument is depicted in Fig. 304, and a cross-section on a slightly larger scale is shown in Fig. 305. At the back of a mouthpiece *e* which collects and concentrates the sound-waves there is placed a thin disc *c c* of ferrotype-iron, such as is sometimes used by photographers; the disc is clamped firmly round the rim, but its central portions are free to vibrate. Immediately behind the disc is one pole of a straight steel bar-magnet *m*, which runs down the centre of the handle and can be moved nearer to or farther from the disc by the screw at the far end. Surrounding the forward pole of the bar-magnet, in a chamber hollowed out behind the disc, is a coil *b b* of fine insulated wire, the ends of which are connected by means of the wires *d d* passing through the handle to the binding screws V V, which are the electrical terminals of the instrument.

It will be observed that this wonderful instrument is extremely simple, and consists of very few parts. How, then, can it produce such astonishing results? A careful consideration only makes us the more astonished as we realise how wonderfully subtle Faraday's law of magneto-electric induction is in its far-reaching consequences. One way of stating this law is to say that whenever magnetic lines of force cut conductors, electric pressures or E.M.F.'s are set up in these conductors. Apply this to the case before us. The soft iron disc *c c*, by its presence opposite the pole of the magnet *m*, modifies the magnetic field in the neighbourhood of that pole, the lines being drawn into the iron in the manner already fully described in preceding chapters. Now when this disc is set in vibration by the sound-waves impinging on it, its various portions swing backwards and forwards in the field of the magnet. To every position of the disc there corresponds a definite distribution of the field, and thus, as the disc is continually changing its position by vibration, so will the magnetic lines of the field be thrown into a state of tremor in which they will be continually cutting the conducting wires of the coil *bb* and setting up E.M.F.'s therein proportional in magnitude and direction to the *rate* of cutting. If, therefore, *b b* form part of a closed circuit there will be set up in this circuit vibrating or, as we prefer to call them, alternate currents, which follow the E.M.F.'s through all their changes.

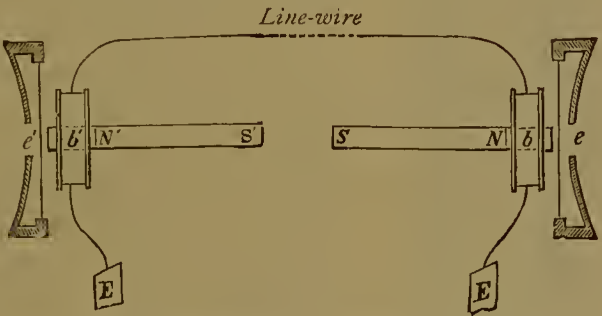


Fig. 306.—Diagram of Bell Transmitter and Receiver.

To understand how these currents again give rise to sound-waves, consider a similar instrument fixed in the circuit of *b b*, as shown at *b′* in Fig. 306. The alternate currents passing round the coil *b′* alternately strengthen and weaken the magnetism of the pole N′ of the magnet N′S′, and thus affect the distribution of the field in its neighbourhood. In this field is another soft iron disc similarly placed to that in the transmitter, and the varying attractions on this disc, due to the varying field, set it in vibration in such a manner that the air in the mouthpiece *e′* becomes agitated with sound-waves similar to those originally directed into the distant mouthpiece *e*.

But though we can thus follow in detail the various transformations—acoustical, mechanical, magnetic, and electrical—which take place, a thoughtful mind cannot but be lost in profound wonder at the faithfulness with which each effect follows the cause producing it through all the delicate complexities of its multitudinous changes; and, as before remarked, the astonishing aspect is, not that the sounds heard at the distant end should not be exactly the same as those thrown into the transmitter, but that any recognisable articulation at all should survive through so varied a course of transformations and transmissions.

Such was the Magneto Telephone as given to the world by Graham Bell in 1876. As already remarked, the instrument had to play the part both of a transmitter and a receiver. In the former function it has been superseded by a class of instruments depending upon a different principle of action; but as a receiver the Bell Telephone, in some of its numerous modifications, is still the most reliable and best instrument.

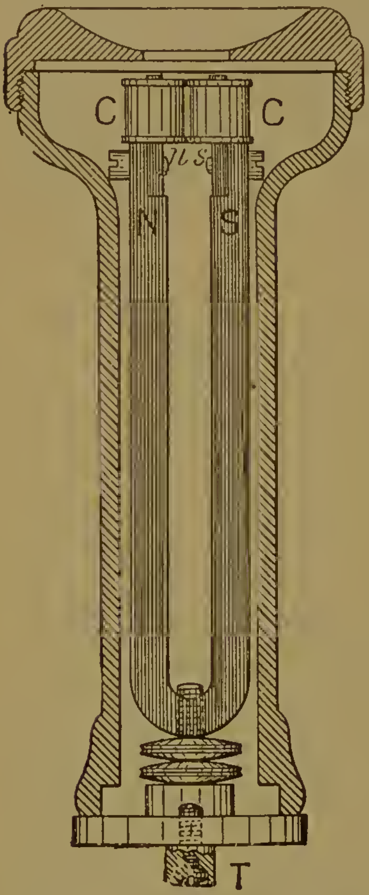


Fig. 307.—The Double-Pole Bell Telephone.

These modifications, whether made by the original inventor himself or by others, are not very fundamental. The most striking consists in bringing two magnetic poles of opposite kinds near the disc, so that the latter plays a more important part in the magnetic circuit, and therefore the variations of its position become more effective. One of the latest forms of such a double-pole telephone is shown in Fig. 307, which represents the pattern manufactured by the Western Electric Company. Instead of the straight bar-magnet of Fig. 305, we have a steel horse-shoe magnet N S, having soft iron polar extensions *n s* clamped on to it, with their ends coming very near the ferrotype disc. The coils C C are slipped over these polar extensions, their ends being brought to the terminals T, as in the original Bell telephone. The outer case is of ebonite, the mouth-piece being screwed on as shown. A packing ring of blotting-paper is often interposed between the ebonite and the disc, enabling the latter to be more firmly and softly clamped.

As illustrating the modifications in form which the instrument may take, Fig. 308 represents the "Ader" pattern. In this the magnet M is circular, and forms the handle by which the telephone is held. This magnet has also soft iron polar extensions, on which the coils *s s* are placed. Another feature is the presence of a comparatively massive ring *a a* of soft iron fixed to the back of the mouth-piece, and close to the iron disc on its outer side. The presence of this ring improves the magnetic circuit, and causes more lines to flow across the disc, which thus vibrates in a more concentrated field.

Many other variations of the Bell telephone have been invented, some of them merely with the object of evading the patents; but the above examples will be sufficient to explain the fundamental principles upon which the action of all of them depends.

Telephonic Transmitters.—Turning now to transmitters, consider carefully the preceding explanation of the action of the Bell telephone when used as a transmitter, and it will appear that the true function and object of such an instrument is to impress upon the current in the transmitting line wire fluctuations accurately corresponding in phase and period with the movements of the air particles which constitute the sound waves. The Bell telephone accomplishes this object by generating in the electric circuit E.M.F.'s of the required phase and period, which give rise to corresponding currents, somewhat altered, however, by the effects of self-induction and capacity, as already explained in the section on alternate currents.

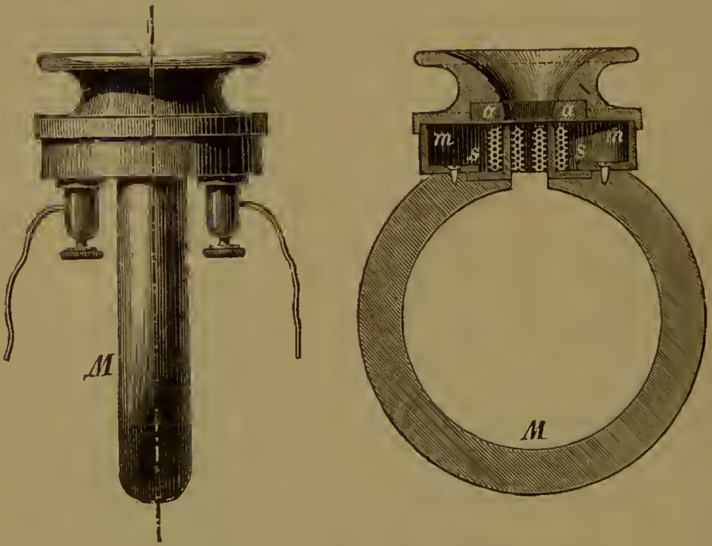
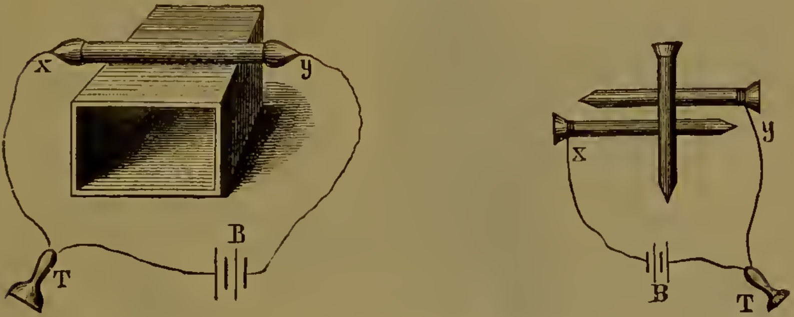


Fig. 308.—The "Ader" Receiver.

But there is obviously another way of causing the required variations of current, and that is to put a source of steady E.M.F. in the circuit and then to vary the circuit resistance so as to produce the desired effect. It is clearly necessary that the variations of resistance should be produced directly or indirectly by the action of the sound waves. The method was used by Edison in 1877 in a *carbon transmitter*, in which a plate or disc, thrown into vibration by the sound waves, was caused to press against a carbon button placed behind it and included in the circuit.

The whole subject was, however, carefully investigated in the following year by Professor D. E. Hughes in a series of masterly researches, which led to the invention of the *microphone*. During these researches, Hughes showed that the effect in Edison's carbon transmitter was due not to an alteration in the resistance of the carbon, as the inventor had supposed, but to the variation in the resistance of the *loose contact* between the carbon and the vibrating plate, this contact being part of the electric circuit. Still further, Hughes showed that the resistance of *any* loose contact which is part of an electric circuit is peculiarly sensitive to disturbances caused by sound waves, and that it very faithfully follows these disturbances through all their complexities. Such arrangements of loose contacts he called **Microphones**.



Figs. 309 and 310.—Hughes' Metallic Microphones.

For instance, the very simple arrangements shown in Figs. 309 and 310 are capable of producing microphonic effects. In Fig. 309, *xy* is a glass tube about 3 inches long, loosely filled with bronze powder, which is kept in by two plugs of retort carbon, connected by wires to a Bell telephone T and a battery B. The tube is placed on a resonance-box to increase the disturbance. In Fig. 310, three French nails are placed, one lying across the other two as shown, the latter *xy* being connected to the telephone and the battery. When the contacts in either arrangement are disturbed by sound-waves, their resistances alter, and the current in the circuit is varied, causing sounds to be heard in the telephone in the manner previously explained.

Greater sensitiveness and more satisfactory results are, however, obtained by using the carbon microphone shown in Fig. 311. Here a rod A of hard carbon, with pointed ends, is loosely held between two carbon blocks C C, which are slightly hollowed out to receive it. The carbon blocks are connected by the wires *x* and *y* to a telephone receiver and battery, as before. The microphone should be stood on cotton-wool or indiarubber, and is very sensitive to sound-effects. For instance, the tramp of a fly walking across the base D can be distinctly heard in the distant telephone.

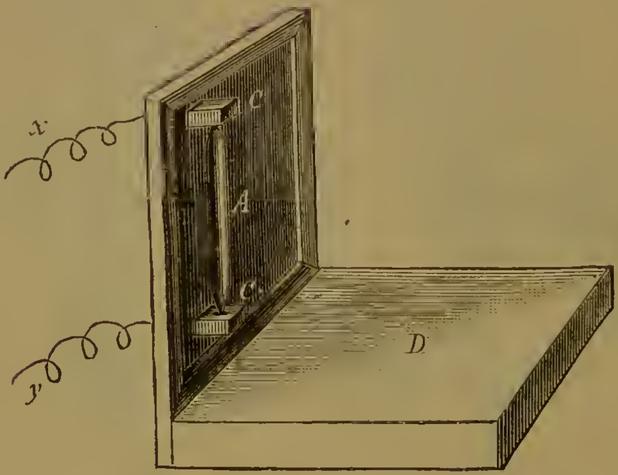


Fig. 311.—Hughes' Carbon Microphone.

The arrangements just described are chiefly of scientific and experimental interest, as showing what crude apparatus can produce astonishing effects. For the clear and distinct transmission of articulate sounds additional precautions and more careful attention to details is necessary. But the fundamental conditions are so simple that an almost infinite variety of detail is possible, and therefore it is not surprising that numerous inventors have more or less successfully occupied the field. Only a few of the most interesting and widely used instruments can be described here.

The Edison carbon transmitter (Fig. 312) is of historical interest, because of its invention before Hughes' microphonic investigations. A membrane D, stretched behind a mouthpiece, presses against an aluminium or ivory knob A, attached to a glass plate G; the latter is glued to a platinum plate P, behind which is the carbon disc C, resting against a solid metal backing. The plate P and the metal backing form the electrodes of the instrument, and the current passes from one to the other through the carbon disc C. The contact resistance between P and C is varied by the varying pressures caused by the vibrations of D, transmitted to P through A and G, and thus the battery-current flowing is caused to vary, as the result shows, with almost perfect synchronism.

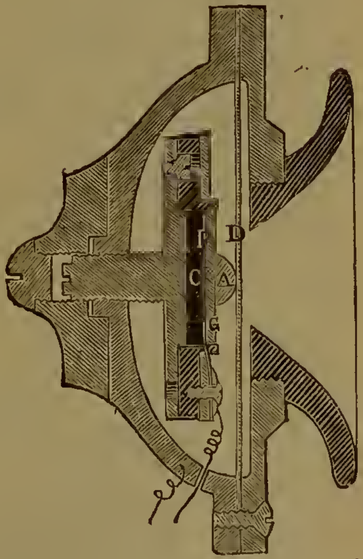


Fig. 312.—Edison's Carbon Transmitter.

Of the numerous microphonic transmitters which followed Hughes' discoveries, and which employed the carbon pencil of Fig. 311, we must be content to describe one only. The lower part of Fig. 313 represents the outside appearance of the Crossley transmitter, and the upper part, on a larger scale, the back of the sloping desk. The central part of this desk consists of a thin pine board D, on the back of which the microphonic pencils are mounted. There are four of these, with their ends resting on four carbon blocks, and arranged electrically, two in parallel and two in series. The current is passed through between metallic clamps attached to the right and left-hand blocks, and when the board is spoken to, its vibrations shake the loosely-mounted carbon pencils, thus altering the resistance of the circuit

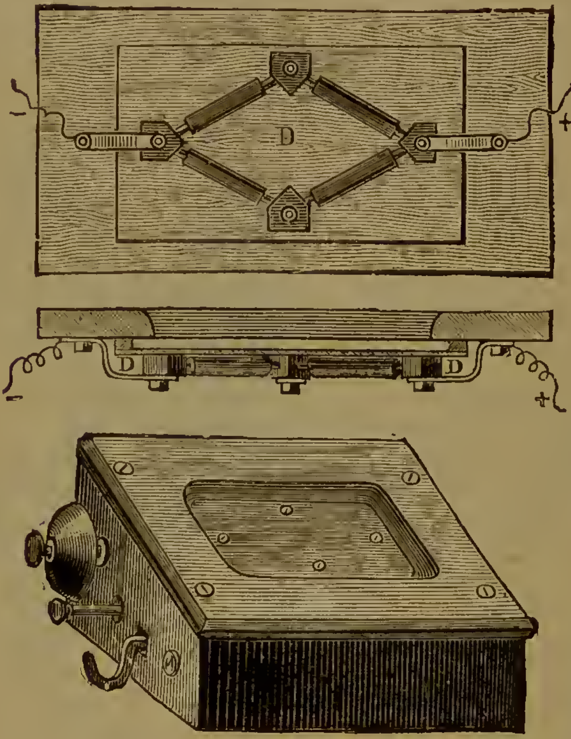


Fig. 313.—Crossley's Carbon Pencil Transmitter.

and the magnitude of the current. A section is also given showing how the board D is mounted behind the opening in the desk, indiarubber being interposed between the two.

A very widely-used form, more nearly resembling the original Edison instrument, is the Blake transmitter (Fig. 314). An iron disc M M, with its periphery covered with indiarubber, is clamped behind a mouth-piece B hollowed out in the solid wooden front. This front also carries a metallic ring A, with arms projecting at the top and bottom. The top arm carries a stiff brass spring F′, to which is attached the metal piece W, having the shape shown, and with its bottom shoulder resting against the end of the adjusting-screw S. To this metal piece are attached two springs F and *f*; the former, electrically connected to W, carries a brass button *m*, in a recess in the front of which is placed a button of compressed carbon shown black in the figure. The other and lighter spring *f* is insulated from W, and carries a platinum contact *p*, interposed between the carbon button and the iron plate M. The current is passed through the contact between the platinum and the carbon,

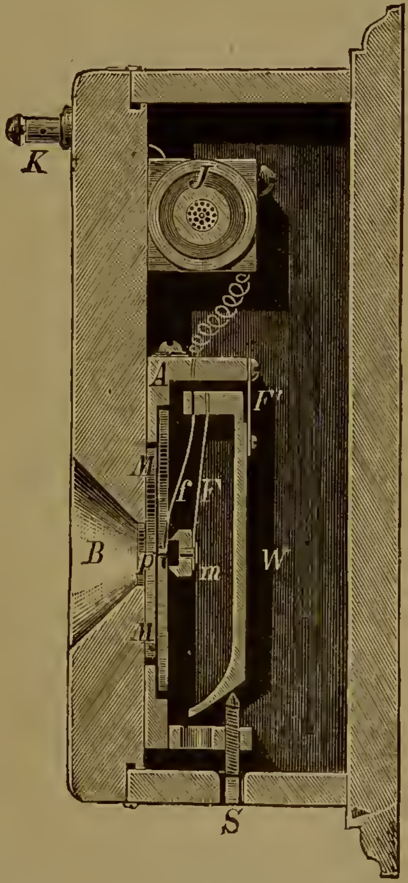


Fig. 314.—Blake's Microphonic Transmitter.

and is varied by the vibrations of M. It also passes through the primary of the induction coil J, whose function will be explained later on.

One of the simplest transmitters, and one which, in its various modifications, is now widely used, especially for long-distance working, is the Hunning's transmitter (Fig. 315), invented by an English clergyman in 1878. A small hollow chamber, about $2\frac{1}{4}$ inches in diameter, in a block of wood has a plate B of carbon or platinum fixed at the back, and electrically connected to the binding-screw C′. The rest of the chamber, which is then only from $\frac{1}{16}$ to $\frac{1}{8}$ inch deep, is loosely filled with granulated carbon free from dust, on the top of which is placed a diaphragm D of platinum foil. The diaphragm is held in its place by the metal ring A A, connected to the terminal C, and clamped down by the block of wood, out of which the mouth-piece is hollowed. Opposite the bottom of the mouth-piece the diaphragm is protected from injury by a piece of wire gauze. The current is passed from D to B through the granulated carbon, and the microphonic effects are excellent, probably because of the numerous contact points, both at the electrodes and within the mass of the carbon.

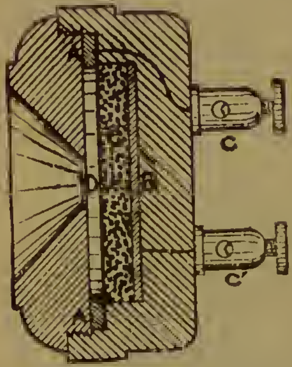


Fig. 315.—The Hunning's Granular Transmitter.

The transmitters above described include most, if not all, of the leading types which, in some form or another, are now in actual use. The variations in details are almost endless, and many of these variations are exceedingly important, for the whole effect produced being due to the operation of a multitude of very minute causes, it is obvious that small changes in the arrangement or proportions of the parts may have a considerable influence on the effect. But these are details which are chiefly of technical interest, and the foregoing will probably enable the reader to readily follow any of them which may come under his notice.

The Induction Coil or Transformer.—An essential feature of microphonic transmission is an induction coil, in the primary or thick wire circuit of which the battery and microphonic contacts are placed, whilst the transmitting line is attached to the ends of the secondary circuit.

The principles and the construction of induction coils are fully explained in the next chapter in connection with the alternate-current transformer. For our present purpose we may explain that the transformer (sometimes called a *translator*) used in telephonic work consists of a bundle of fine iron wires surrounded by two solenoids, one consisting of a few turns of comparatively thick wire, and referred to as the *primary* circuit, and the other of many turns of fine wire known as the *secondary* circuit. If a current in the primary is caused to fluctuate in any way, then, as fully explained later on,[1] E.M.F.'s are generated in the secondary, having periods and phases corresponding to those of the fluctuations.

Now in a microphone the fluctuations of the current are caused by the fluctuations of the resistance of the carbon contacts. The actual resistances affected are not very great as measured in ohms, and, therefore, for their mere fluctuation to produce a great variation of current, it is obvious that the whole resistance of the circuit must be small. For instance, if the largest change produced in the transmitter be as great as one ohm, and the whole circuit have a resistance of 1,000 ohms, the change in the current will only be $\frac{1}{1000}$ part of its actual magnitude; whereas if the circuit resistance be as low as 10 or 20 ohms the change will be $\frac{1}{10}$, or $\frac{1}{20}$ of the whole current, and, therefore, relatively of much greater importance.

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[1] Page 680, *et seq.*

But with such a low resistance in the circuit it would be impossible for the transmitting line to be very long, and microphonic transmitters could only be used for short distances. The induction coil surmounts this difficulty. The battery circuit passes only through the microphone and the primary of the induction coil, and therefore may be made to have as low a resistance as may be desired. Thus the fluctuations of the current in this circuit may be made very large in comparison with the total current. It is the *rate and magnitude* of these fluctuations which determine the E.M.F.'s induced in each turn of wire in the secondary circuit, and as we may have a very large number of turns, all electrically in series, we may raise the total E.M.F. for any particular fluctuation in the primary to any value we please. Thus the secondary being connected through the line to the distant receiver, these E.M.F.'s give rise to the desired currents in the coils of the latter. By careful attention to the essential details it is in this way possible to talk over a distance of more than 1,000 miles.

TELEPHONE SETS.

Having now described the chief characteristics of the distinctive instruments, it is next necessary to show how these are combined and connected so that they may be available for ordinary intercommunications. Every user of the telephone obviously requires as a minimum equipment a transmitter and a receiver, together with some method of calling the attention of, or "ringing-up," his distant friend when he desires to speak to him. Moreover, these instruments must be permanently connected with the different circuits, properly joined, and provided with the necessary batteries, switches, etc., arranged on a simple and easily worked plan.

There are, of course, many ways of accomplishing these objects; but for our purpose the description of one well-designed "Telephone Set" will be sufficient. We select the apparatus used by the British Post Office, which has the advantage of being available for many requirements of telephonic work.

The base of the apparatus is shown in Fig. 316 with the cover removed, the cover, which carries the microphone on its under side, being shown in Fig. 317 in the position in which it would be seen if raised from the base board and slightly tilted so as to expose the microphone. Lastly, the electrical connections are shown in Fig. 318. The letters in Figs. 316 and 318 correspond.

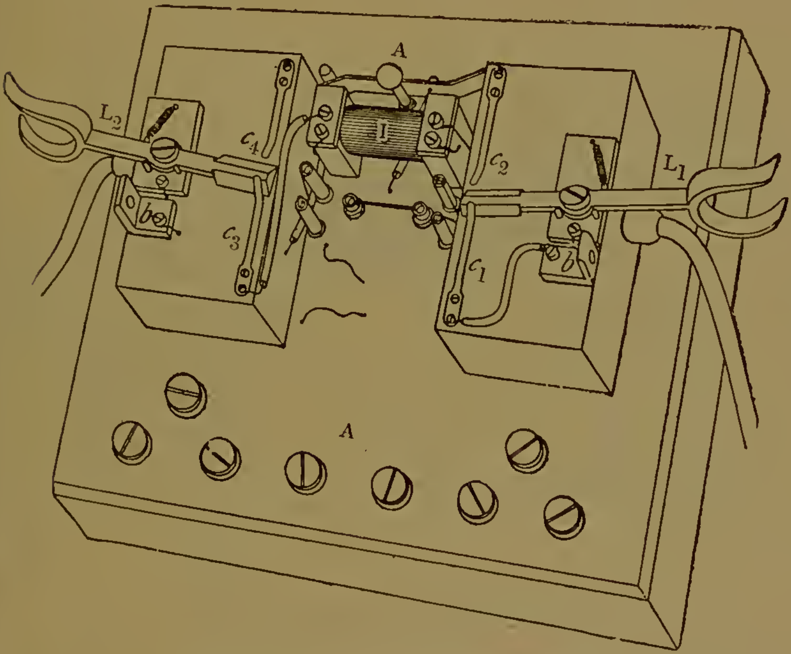


Fig. 316.—Base of Post Office Telephone Set.

The external connections are made by means of the screws in front, which are outside the cover when the latter is in place. For simple working on short lines an ordinary trembling bell is attached to screws 1 and 3, the line wires to 4 and 5, and a split-battery (*i.e.* a battery divided into two sections) to 5, 6, and 7, whilst 2 and 8 are left unconnected.

The position indicated is that for receiving a "call." The receivers R R are hanging on the hooks of the switches, pulling down the outside ends of the levers, and bringing the other ends into contact with the springs c_2 and c_1 respectively. The current from the "ringer-up," entering from the line-wire at 4, passes through the spring *p* at the back to the middle of the lever L_2, thence through the contact spring c_1 and the wire *s* to terminal 1, from which it passes through and rings the bell; it then reaches 3, whence it passes through the contact spring c_2 and the middle of lever L_1 to terminal 5, and so back to the distant ringer.

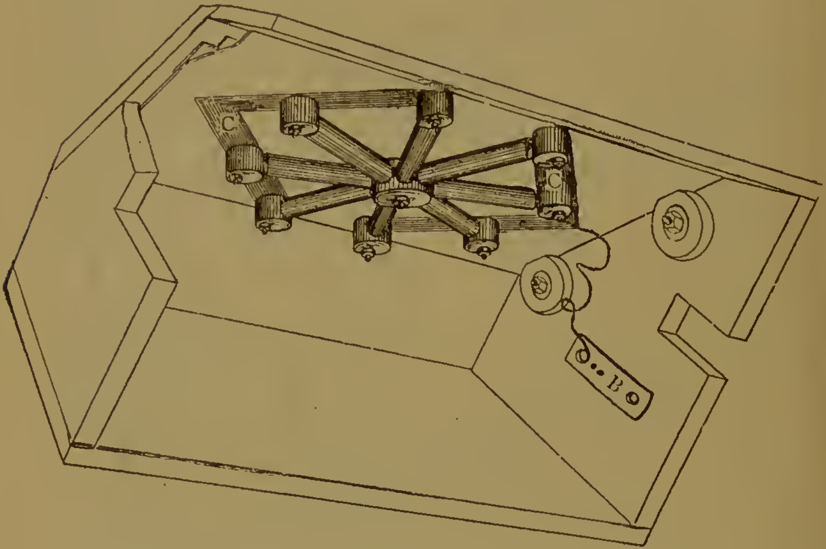


Fig. 317.—Cover and Microphone of the Post Office Telephone Set.

Thus the bell is rung, and the attention being called, the receivers R R are lifted off the hooks and the levers L_1 L_2, being relieved of their weight, are drawn over by springs so as to break contact with c_2 and c_4 and make contact with c_1 and c_3 instead. This change directs the received current through a totally different course. Arriving, as before, at 4, and going through p to the middle of L_2, it now passes to the contact spring c_3, thence through the secondary or fine wire of the induction coil to the receiving telephones R R, which are electrically in parallel; it then passes through the middle of lever L_1 back to the line through terminal 5. Thus the fluctuating currents on the line pass through the receivers, held one to each ear, and the message should therefore be distinctly heard.

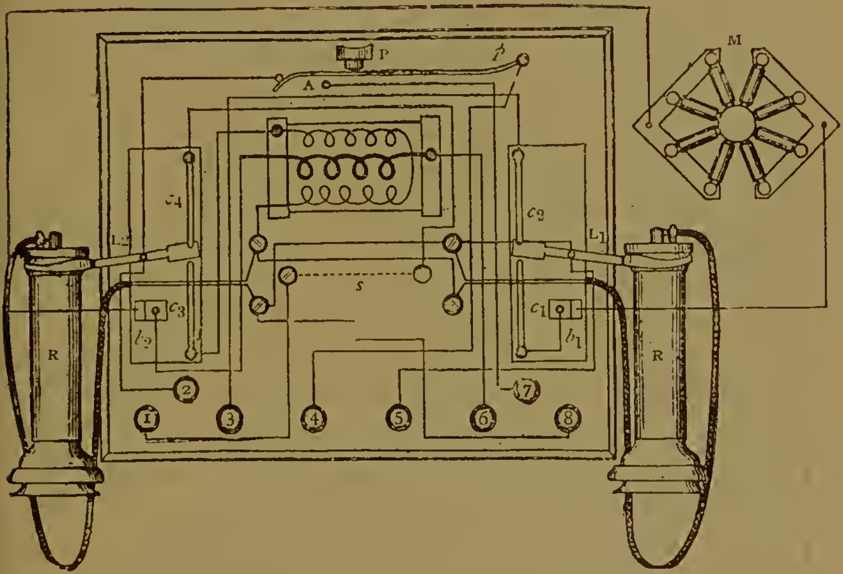


Fig. 318.—Connections for Simple Working.

In talking back, the user talks clearly and distinctly and in an ordinary conversational tone, without shouting, towards the deal board, on the back of which the microphone M is placed. This microphone is in the circuit of one of the sections of the battery, which, starting from 5, passes through the middle of lever L_1 to the contact spring c_1 and the block b_1; from here it passes through the microphone M, the block b_2, and the primary or thick wire of the induction coil back to the battery by way of terminal 6. The agitation of the microphone contacts causes the current in this circuit to vary, and its fluctuations affect the secondary circuit of the induction coil, setting up E.M.F.'s therein. As this secondary is part of the circuit above described for the received currents, these E.M.F.'s transmit through that circuit and the line telephonic currents which are received at the distant station.

One other circuit has still to be traced, viz., that for ringing-up the distant correspondent. The receivers R R being placed back on the hooks, if the button P be pressed the spring *p* changes its contacts to A and closes the following circuit. Starting from terminal 5, the current from the battery goes to line and rings the bell at the distant end, returning by way of 4 through *p* and A to the terminal 7 and the battery. It will be noticed that whilst the full battery is used for ringing-up, only part of it is used for the microphone circuit. This is because the former operation has to be accomplished through a circuit of much greater resistance than exists in the circuit of the latter.

With the same internal connections the apparatus can be used for exchange work or at an intermediate office; and, if necessary, a relay can be inserted for ringing-up if the line circuit is long or of too high resistance.

TELEPHONE EXCHANGES.

The possession of the necessary transmitters and receivers, properly connected up with switches and batteries, though indispensable, is by no means the only important item necessary for complete telephonic intercommunication.

Without the necessary conducting circuits communication would be impossible, and a little reflection will show that, however wealthy a man may be, it is practically impossible for him to run all the circuits that he would require for his daily use even within the radius of a single town, not to mention the extension of his communications to towns in distant parts of the country. It is, of course, possible for a man or a firm to own two or three private lines connecting special points, or to set up a system of circuits within the bounds of a large factory or mercantile establishment; but the practical limit of extension in these directions is soon reached.

The provision of the necessary conducting circuits therefore naturally becomes the function either of the Government of the country or of public companies formed for the express purpose, these recouping themselves, or earning a dividend on their capital expenditure, by charging a toll or rent to the persons who use the circuits.

But in providing the circuits another consideration very soon becomes prominent. Every subscriber or renter paying for the privilege of using a certain system of circuits may not unreasonably desire that it should be possible for him to communicate with each and every other subscriber on that system. But to run a separate circuit for every *pair* of subscribers, even though their actual numbers were small, would lead to an expenditure that would soon make the rent prohibitive, and which, moreover, would increase far more rapidly than the number of subscribers. Thus, for 25 subscribers 300 circuits would be required, for 50 there would have to be 1,225 circuits, whilst for the comparatively small number of 100 no fewer than 4,950 separate circuits would have to be provided.

This difficulty has been met in a way which, in principle, is remarkably simple. Each subscriber to the system is provided with a single circuit, and the ends of all these circuits are brought to some central point. Here the circuit of any one subscriber can be temporarily joined to the circuit of any other, as and when required, forming then one complete circuit between the two subscribers, the connection being broken when the conversation is finished. The central place or room, to which all the individual circuits run, is known as the "Telephone Exchange"; and where the subscribers are very numerous, or spread over a large area, it is found economical to have more than one "exchange," the various exchanges being connected by trunk lines, as they are called, so that still any subscriber can be put in communication with any other on the system.

Though the art of telephonic communication, counted by years, is still in its infancy, numerous systems—some complicated, some simple—have been industriously devised to quickly and simply perform the changes and make the necessary connections at the exchange. The description of these various systems, with all their details, would alone fill a fair-sized book, and we shall therefore confine our remarks to indicating the chief characteristics of one of the most recent.

Before doing this, it will perhaps tend to clearness if we first summarise the various requirements that an exchange must necessarily fulfil. First, the subscriber must be able to "ring up" the exchange—that is, the attention of the attendant must be called to the fact that a certain subscriber, usually indicated by a numeral, desires to converse. The attendant has then to talk with the subscriber and ascertain which other subscriber he wishes to communicate with. The attendant must then find out whether the other subscriber's line is at liberty, and, if so, connect the two lines together in such a way that *the conversation passing cannot be overheard in the exchange.* This proviso is *very important.* When the conversation is finished, the attendant must be apprised of the fact, so that he may disconnect the lines. Thus, though the main idea is simple, a fair number of subsidiary operations have to be provided for.

The description of the switch-board on which the various changes are made will be more easily followed after one or two subsidiary pieces of apparatus have been described. Of these the simplest is the *cord-peg* shown, full size, in Fig. 319, where the upper figure represents the outside appearance, and the lower one shows the peg with the shield *t* removed. This latter part is of metal of the shape shown; the small cylindric projection C, with its terminal knob, is for making connection with the contacts and springs behind the switch-board. A flexible insulated conductor enters the peg centrally at the other end, and, passing through a bored-out space, is made fast electrically to the screw S.

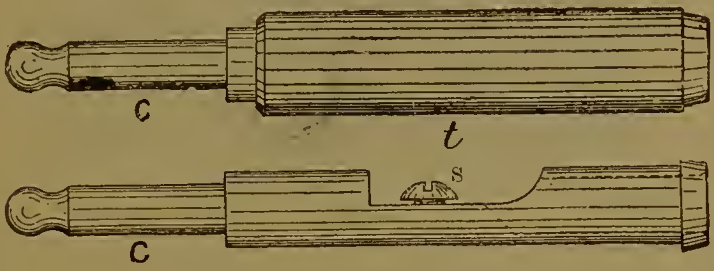


Fig. 319.—The Cord-peg Connector.

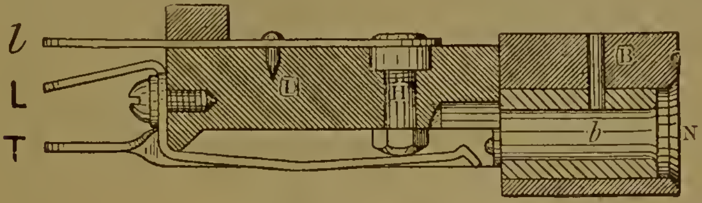


Fig. 320.—Section of a Switch-spring.

The *switch springs*, which are operated upon by the cord-peg, are shown in section in Fig. 320. B represents the wooden front of the switch-board, into which the brass tube *b* is inserted, giving the front of the board the appearance seen, full size, in Fig. 321, where three such holes, properly numbered, are shown. The block D projects from the back of the board, and carries the separate brass strips *l*, L, and T. Of these, the strip *l*, when no peg is in the hole N, is in contact with L by means of the small bolt H. The strip T is soldered to the tube *b*, and passes to the back without touching L. When a cord-peg is inserted in N, the knob at its end presses against the inclined end of the strip L lying immediately behind the hole, and makes good contact with it, at the same time pushing it out of the contact with the bolt H. The connection between it and *l* is therefore broken, and simultaneously the flexible conductor at the other end of the peg is electrically connected to L.

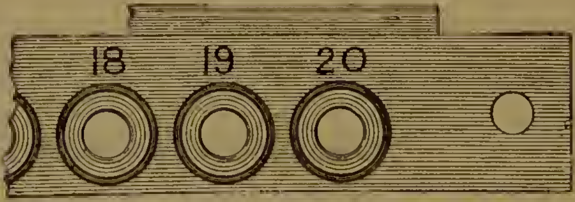


Fig. 321.—The Switch-Springs seen from the front.

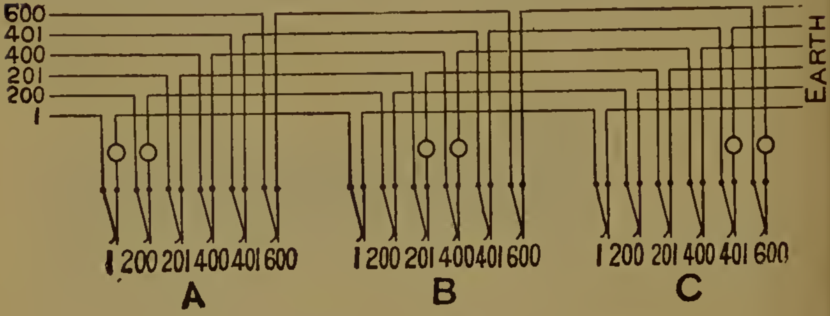


Fig. 322.—Principle of the "Multiple" Switch-Board.

Turning now for a moment to the general electrical plan of the board, the principle used is shown diagrammatically in Fig. 322. The whole switch-board is divided into sections, of which three, A, B and C, are shown in the figure, where, to avoid confusion, only the wires for six subscribers appear. Each subscriber has a switch spring similarly numbered on each section of the board. For instance, if the wire marked 401 on the left be traced, it will be found to run through a numbered pair of springs at each section, and to be finally put to earth after passing C.

The line-wire of each subscriber therefore passes behind each section of the switch-board, and in each enters the appropriate switch-spring by the strip L (Fig. 320), and leaves it by the strip *l*. Each section is in charge of a separate attendant, but, though all the wires run to each section, the call apparatus for the various subscribers is divided between them. Thus, subscribers 1 to 200 have their call indicators, etc., fixed on section A, 201 to 400 on section B, and so on. As a matter of fact, each subscriber belonging to section A has *two* switch-springs on that section, one in its proper position amongst the springs of all the other subscribers on the board, and the other, known as his "local," in a separate part of the section. Attendant A can therefore only be "rung-up" by subscribers 1 to 200, but, having ascertained the wishes of the ringer-up, he can put him in communication with any other subscriber on the board by simply inserting the two pegs at the end of the same flexible conductor in the corresponding holes, thus bringing the line-wires of each into electrical connection through the strips L, the pegs, and the flexible conducting cord.

Having explained the general plan of the board, we may now show the electrical position of the rest of the apparatus, and for this purpose are traced in Fig. 323 the connections of a line (No. 927) through four sections, D, E, F and G, of the board. As already explained, each of these sections contains 200 "locals," as shown by the numbers attached, but all the subscribers have switch-springs on each section. The "local" and indicator for No. 927, the wire traced, will be found on section E (801 to 1,000); but before reaching that section, it has already passed through switch-springs on the preceding sections. On E it passes through a switch-spring in the same position as on the other boards, and also through another marked "local" in a different part of the section. After passing the local, it passes through switch-springs on each of the remaining sections, and then returns to the indicator on section E, after which it is put to earth to complete the circuit. A cord-peg is shown inserted on section F, in order to connect 927 to some other subscriber whose local is on that section. The effect of this is to disconnect 927 from his indicator and its earth, and to put him on to the test-wire, as well as in connection with his correspondent. His connection to the test-wire enables any of the switch-board operators on the other sections, by applying a simple test, to ascertain that wire 927 is engaged, thus preventing awkward mistakes.

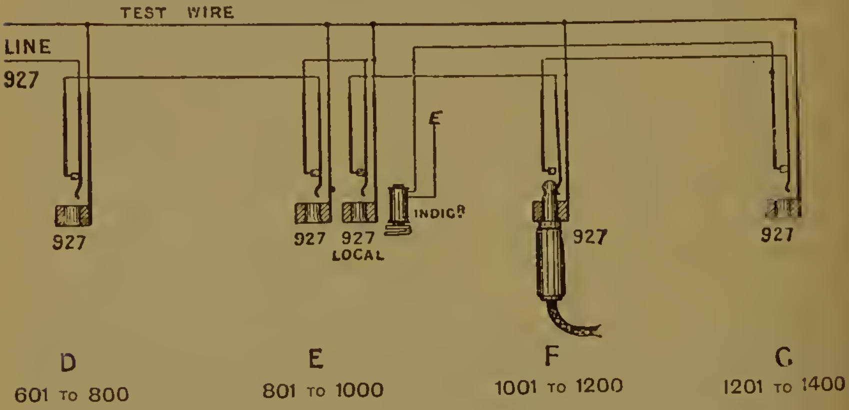
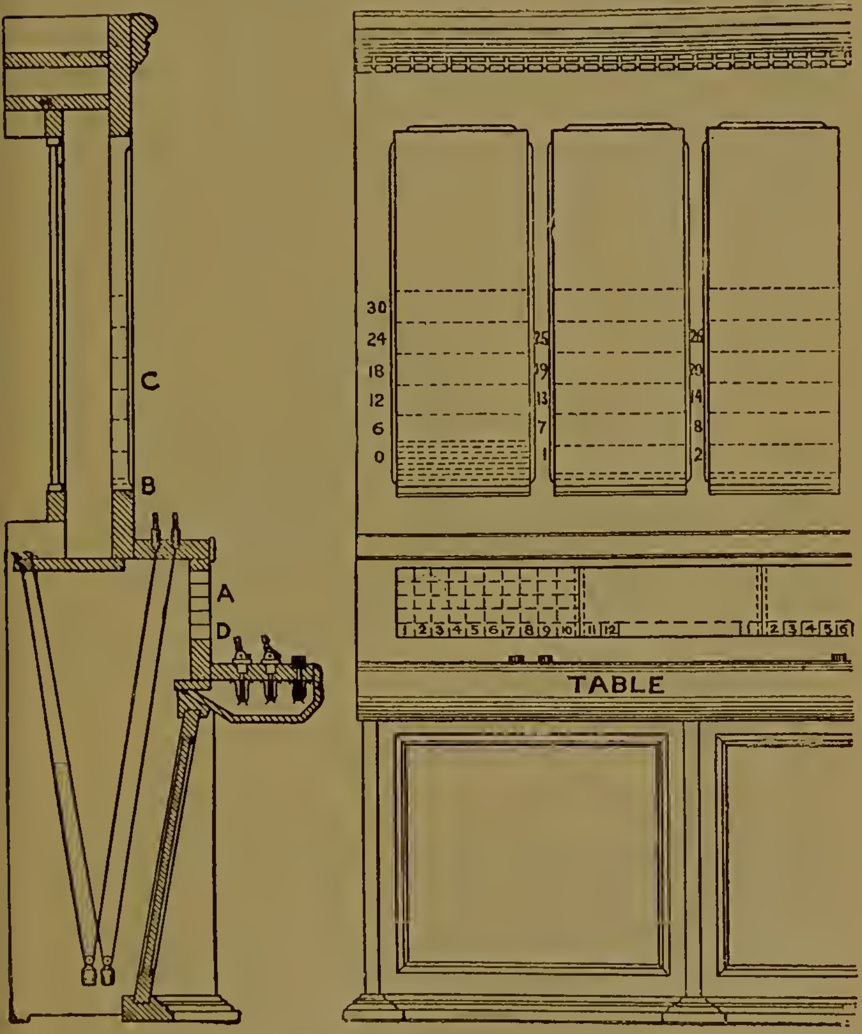


Fig. 323.—Connections of a single line on the Board.

It will now be possible to understand the arrangement of the switch-board itself, which is shown in sectional



Figs. 324 and 325.—Sectional and Front Elevation of a Multiple Switch-Board.

elevation in Fig. 324, and in front elevation in Fig. 325. The figures represent a Western Electric multiple switch-board. The indicators of the subscribers belonging to any section are at A, and the "local" switch-springs already referred to are at B, both within easy reach of the operator sitting in front of the table. At C are the switch-springs of all the subscribers on the exchange arranged in hundreds, in the manner partly shown in Fig. 321, so that any required spring can be quickly found. At D are the "ring-off" indicators —*i.e.* the indicators which show when the conversation is finished, and that the connections may be broken.

The construction and mode of action of the "indicators" has still to be explained. Of these there are very numerous patterns, differing in minor, but sometimes important, details. A very good one, known as the "Danvers" pattern, is shown in Fig. 326. A two-limb electro-magnet M, placed behind the indicator-board, has an armature A pivotted as shown, and with an extension passing through a slot in the framework. The front end of the lever is held depressed by a strong spring, which can be adjusted by the screw S, and which thus pulls the armature A off the magnet M when the current is not passing. At the end of this front arm is a catch, which usually engages with the top edge of and holds up the shutter P. But when A is

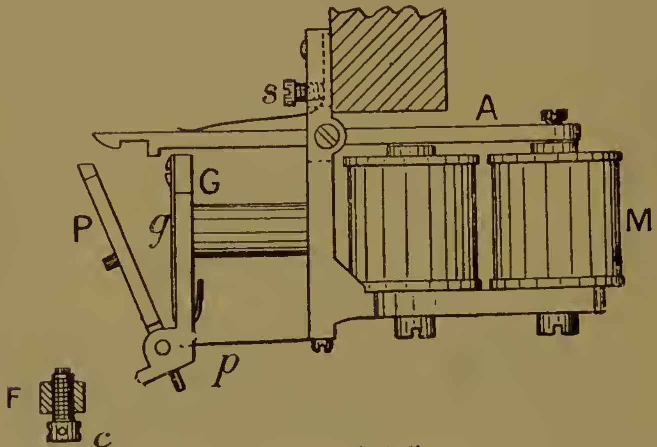


Fig. 326.—Electric Indicator.

attracted by the magnet, the catch is lifted, and the shutter falls by its own weight, exposing the plate G, on which is fixed a number by means of a thin brass frame *g*. The shutter P is shown in the act of falling; when in its lowest position, a platinum point on it rests on the contact screw C, and closes a local circuit in which an electric bell is placed. Such circuits are, however, not used in large exchanges, and the attendant has to watch the fall of the shutter, which exposes the number of the subscriber who has "rung-up."

For simplicity we have described a switch-board with earth returns; where, for reasons given subsequently, complete metallic circuits are desirable, the same principles are used, but the switch-springs and cord-pegs, etc., are necessarily more complicated.

With this we must conclude our remarks on "Telephone Exchanges," and refer our readers to technical books for fuller details. We cannot, however, quit the subject altogether without a brief reference to a most interesting branch, which is at the present time undergoing rapid development.

Long-Distance Telephony.

As soon as we take the conducting circuit of a telephone outside the confines of a single building, or run it in the neighbourhood of wires in which other electric currents are flowing, we are at once met with a number of difficulties, due to the fundamental electrical laws already explained. For instance, when the first telephones brought to this country from America were connected up, for experiments, to one of the telegraphic circuits in the City of London, we are told that the tapping of all the Morse keys in the city could be heard in the receiver, producing such an overwhelming noise that conversation was out of the question. And in the early days of telephonic developments "cross-talk" and noises of all kinds from neighbouring wires were frequent causes of complaint from the subscribers.

All these disturbances are due to the far-reaching character and applicability of the laws of induction, both magneto-electric and electro-static. In the above-mentioned case the telephonic circuit ran alongside the other telegraphic circuits in which numerous and varying currents were being used. The fluctuations in these currents caused lines of force to be continually cutting the telephone circuit, thus giving rise to E.M.F.'s in the latter which set up currents affecting the telephone receiver. This was due to magneto-electric induction; but electro-static induction was also at work, for when a conductor has its potential altered at any point conductors in its neighbourhood have their potential momentarily altered, and currents are set up in the latter until a state of equilibrium is reached. If, therefore, a telephone be placed in the last-named conductor these currents will affect it.

It thus very soon became evident that, if telephony was ever to be practically successful, it was absolutely necessary to *screen* the telephone circuit from such disturbances. A great improvement was effected by abandoning the earth return, so universally used in telegraphy, and employing instead a complete metallic circuit, and though subsequent improvements have enabled earth returns to be employed in certain cases, recourse is now always had to complete metallic circuits wherever good work is desired. In these circuits the two wires should always be close to—and, if possible, twisted round—one another, so that they will both be at the same mean distance from the disturbing cause, which will, therefore, act equally on both in a way that will tend to neutralise its effects on the complete circuit. For instance, in Fig. 327, if the closed loop represents a metallic circuit, a disturbing cause at a distance would produce E.M.F.'s in both wires in the same direction—say, from left to right, as indicated by the arrows 1 and 2. An inspection of the figure will show that if these E.M.F.'s are equal, then, being in the same direction *in space*, they will neutralise one another *in the circuit*, in which they are oppositely directed.

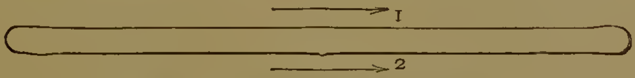


Fig. 327.—Neutralisation of Induction.

To secure the equality of the induced E.M.F.'s the simplest plan is, as we have said, to twist the two wires of the circuit round one another. In wires laid underground this can easily be managed either when the wires are being laid, or, better still, as is now usually done, when the cable containing many wires is manufactured. In the latter case the cable is now generally surrounded by a sheathing of lead connected to earth, which forms the best protection against outside electrostatic induction.

With overhead wires the twisting is not so easily carried out. Two systems have been developed. In the first, known as the "cut and cross-over" system, the wires are at certain intervals cut and fastened-off to the insulators on one of the poles. New wires start from other insulators on the same pole, and are cross-connected to the first wires, so that for the next few spans the position of each conductor is changed relatively to its neighbours. One of these "cross-over" poles,

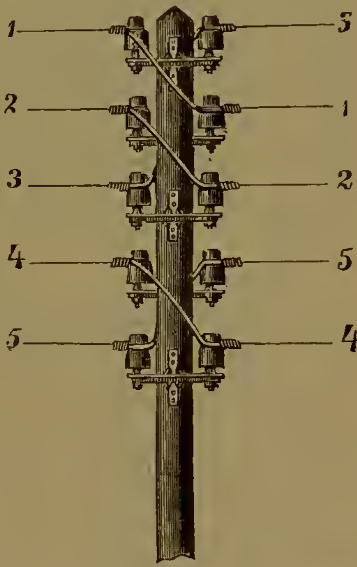


Fig. 328.—Cut and Cross-over System.

with its double set of insulators, is shown in Fig. 328. The corresponding conductors on the two sides of the pole are similarly numbered, and the cross-connecting insulated wires can be traced. In this way the disturbances on any individual conductor due to currents in its neighbours neutralise one another when the whole circuit is taken into account. In practice it is found sufficient to cut and cross-over at the end of every ten or twelve spans.

The other method consists in twisting the wires in the air as they pass from pole to pole, and is illustrated in Fig. 329, which shows two wires so twisted. The plan consists in having long and short arms alternately above and below one another on each pole. In each span each wire crosses over either horizontally from outside to inside (the other wire crossing in the opposite direction) or it crosses vertically from the upper to the lower arm. In this way the wires twist completely round one another once in every four spans.

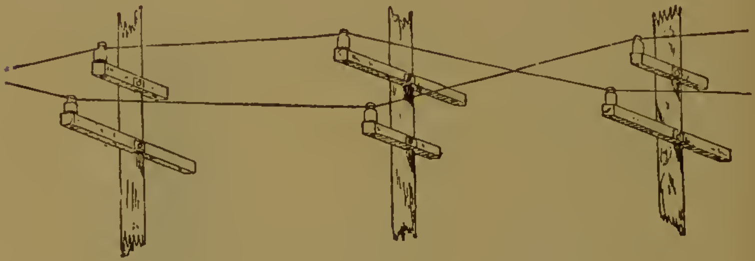


Fig. 329.—Two Wires Twisted to Neutralise Induction.

By carefully attending to details of this kind in the erection of the lines it is now found possible to telephone over long lengths of aërial wires. For such long-distance work special trunk-wires, as they are called, are run: these are now invariably of copper, and are usually much heavier than ordinary telegraph wires, so as to secure minimum resistance. Complete metallic circuits are invariably used.

Such a trunk line has been worked commercially for some time between New York and Chicago, a distance of nearly 1,000 miles. As the cost of the erection of trunk-lines is unusually heavy, a charge that at first sight may appear excessive has generally to be made for the use of them. Thus the New York-Chicago line tariff is 9 dollars (37s. 6d.) for five minutes' conversation.

When we turn to telephony through submarine or subterranean cables a new difficulty appears. We have already referred to the effect of electrostatic capacity in blurring the signals and reducing the speed of working on long ocean telegraphic cables. When, therefore, we remember that the telephonic currents are enormously more rapid in their changes than the comparatively sluggish telegraphic currents, it is not surprising that the problem of long-distance ocean telephony has not yet been practically solved. We may remark, however, that some very promising solutions have recently been proposed; but until these are actually tried with a long and specially-constructed cable, their feasibility cannot be considered as demonstrated.

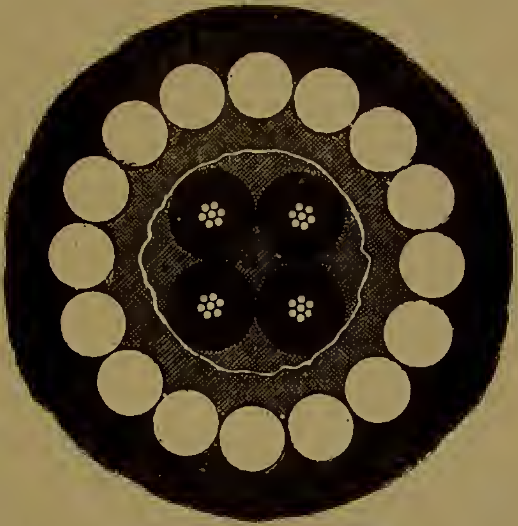


Fig. 330.—Full-size Section of the Irish Telephone Cable.

For short lengths of cable, however, the problem ha been successfully solved. Thus London and Paris are connected by a trunk-line, including 23 miles of specially constructed submarine cable. Also Glasgow and Belfast are similarly connected, the cable span being rather longer than in the preceding case. Both these cables have been carefully designed by the engineers of the British Post Office, and we give in Fig. 330 a full-size section of the Irish one, which is the most recent. The cable contains four conductors, each consisting of seven strands of wire. It therefore has sufficient conductors for two complete circuits, and in working, the two diametrically-opposite ones are joined for one circuit so as to minimise the cross-talk. The four conductors are insulated in the usual way, with gutta-percha, and twisted round one another in long spirals. They are then covered with a serving of tarred hemp and a wrapping of a thin sheathing of brass tape, shown by a fine white line in the section; outside this there comes more tarred hemp, and then the protecting sheathing of stout galvanised iron wires, each having a diameter of 0·28 inch and a breaking-strain of 3,500 lbs. Outside the sheathing is a further protective coating of mineral pitch and sand.

The reason for using the brass tape sheathing is a curious one. In the early days of submarine telegraphy much trouble was caused in tropical waters by the depredations of an insect known as the *teredo*, which has a great predilection for gutta-percha, and which, therefore, soon destroyed the insulation. Latterly, this insect, finding its favourite food plentiful, has made its appearance in British waters; hence the necessity for the brass sheath, which, fortunately, constitutes an effective protection against it. The French cable only differs from the Irish one in the absence of this brass sheath.

With such land and submarine lines telephonic communication is successfully carried on between London and Paris. It is interesting to note that the line consists of 283·5 miles of aërial wires and 27·8 of submarine and subterranean ones, making 311·3 miles in all. More than half the electrostatic capacity of this line is due to the cable, short as it is, so that the line is equivalent electrically, except in resistance, to an overhead one of more than double the length. Experimentally, conversation has been carried on over this cable between London and Marseilles, which is a circuit more than equivalent to the New York-Chicago line.

Minor Applications of the Magnetic Effect.

There are numerous applications of the magnetic effect other than those directly concerned with telegraphy and telephony. When attention has to be called to something occurring at a distant place, or an automatic record has to be made of successive phases of recurring phenomena, or, still more frequently, when one person requires the services of another who is too far away for the voice to reach him, the electric current is an obedient and a wonderfully adaptive servant. Thus, for instance, for fire and burglar alarms, for recording the successive changes in the meteorological elements (temperature, barometer-pressure, etc.), and last, but not least, for domestic use in the shape of call-bells and otherwise, nothing more convenient has hitherto been devised. Nor should we omit to note that for time-keeping purposes a number of clocks electrically controlled can be synchronised with great accuracy.

In many, if not most, of these numerous applications the most prominent piece of electro-magnetic apparatus is the electric bell. There are many varieties adapted to special purposes, but by far the most common is the ordinary "Trembling" bell, one pattern of which is shown in Fig. 331. A two-limb electro-magnet M is mounted on a base-board so that its yoke and armature are vertical, or nearly so. The armature A is attached to a projection on the brass base P by means of a stiff steel spring *f*, so set up that when no current is passing through the magnet A is drawn some little distance away from the poles. Behind A there is another strip of steel, which should be more flexible than *f*, and which is bent outwards so as to come into contact with a pin *c* (projecting from a short pillar) when A is held off the poles. The electric current starting from the terminal screw *a* passes through the coils of the magnet M to the screw *d*, which is in metallic connection with the plate P. It then passes from the supporting projection into the spring *f*, and the other flexible spring to the contact pin *c*, the pillar supporting which is insulated from P; from *c* it goes to the other terminal screw *b*. The armature A carries, by means of a curved extension B, the hammer K, so placed as to strike the gong G when A is attracted to the poles of the magnet.

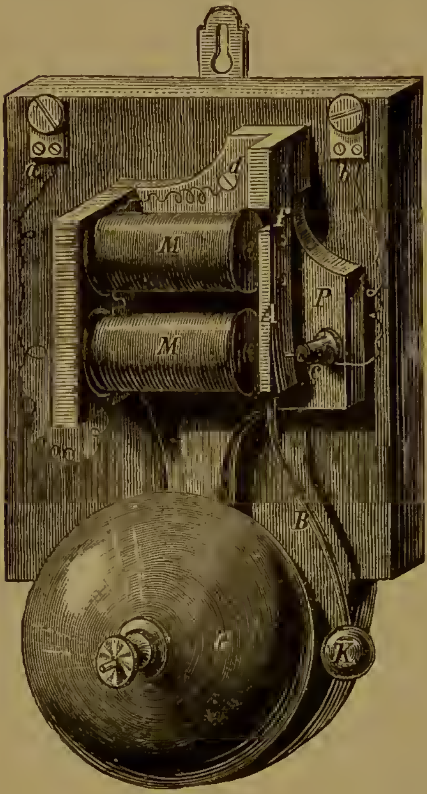


Fig. 331.—The Common or "Trembling" Electric Bell.

If, now, the terminals *a* and *b* be joined to the ends of a circuit containing a battery and suitable circuit-closing devices, whenever the circuit is closed at any pre-arranged point, the current flowing energises the magnet M and attracts the armature A, causing the hammer to strike the gong. But as soon as A has moved a little way forward, the flexible spring behind leaves the contact pin *c* and breaks the circuit. The attraction then ceases, and A is drawn back by the spring *f*. As it travels back the circuit is again made at *c*, the current again passes, A is again attracted, and the gong again struck. These backward and forward movements of A continue as long as current is supplied, and thus the bell continues to ring.

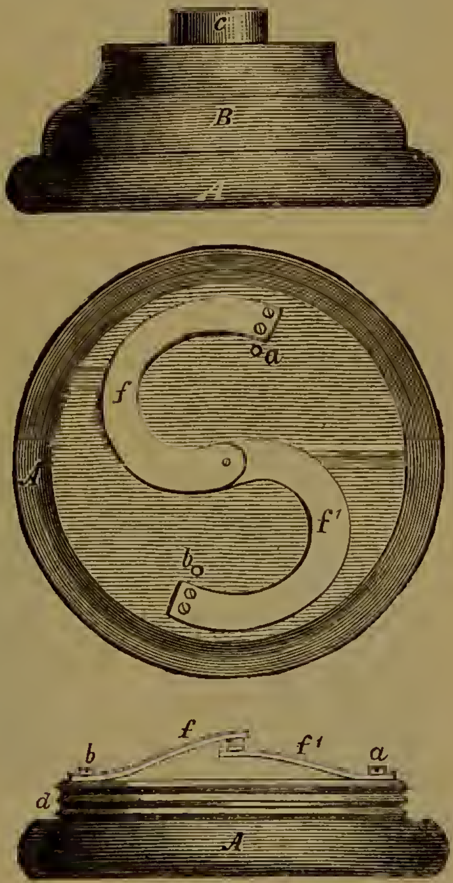


Fig. 332.—The Domestic Switch or "Push."

The apparatus for closing the circuit depends upon the particular requirements. For many domestic purposes the most familiar form of switch is known as the "push switch," or, more shortly, the "push." The outside appearance is shown at the top of Fig. 332, whilst the other two figures show the apparatus in plan and elevation with its cover removed. To a base A of wood, slate, or porcelain, two springs *f* and f^1, of the shape shown, are attached, and to these the electrical conductors, coming through holes *a* and *b* in the base, can be screwed. One spring *f*, as indicated in the elevation, overlaps the other at the centre without touching it. A cover B is screwed on to the screw thread *d*, and in the centre of the cover is a button or push *c*, held from falling out by a flange round its lower edge. Ordinarily *c* rests lightly on *f*, and the circuit is broken by the gap between the two springs. But when *c* is pushed in, the springs are brought into contact and the circuit closed, thus causing the distant bell to ring.

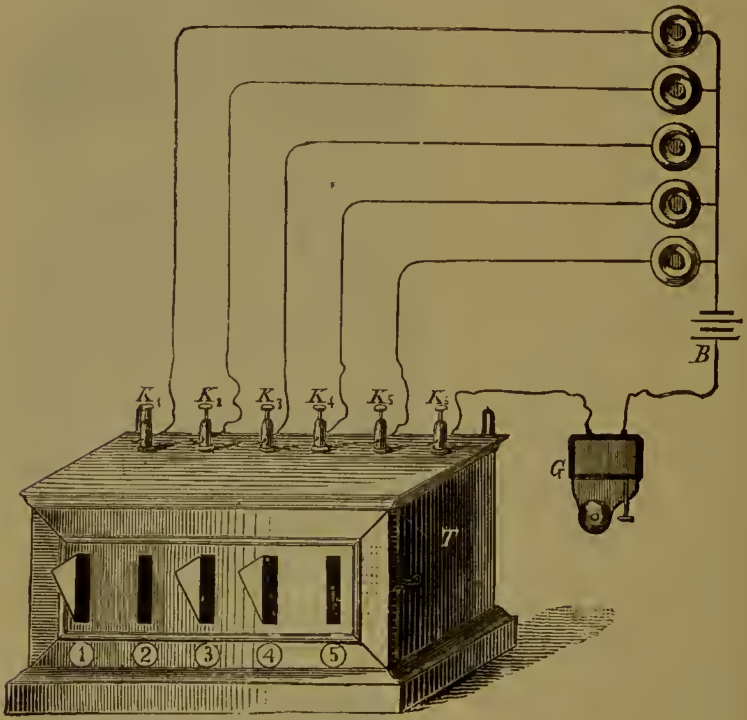


Fig. 333.– Electric Bell Circuits.

The method of connecting-up an electric bell system for ordinary domestic use may interest some of our readers. It is shown diagrammatically in Fig. 333, where it will be observed that only one battery and one bell are needed for the five switches, which are supposed to be in separate rooms. The box T contains the electro-magnets and indicators. Of these there are five sets, one for each circuit. One terminal of each electro-magnet is connected to the common binding-screw K_6, and the other terminal to one only of the five screws K_1—K_5. From these screws the conductors run to the separate pushes in the various rooms. On the other side of the pushes they all join on to a common return-wire, which runs back to the battery. The other pole of the battery is joined through the bell G to the common binding-screw K_6 of the indicator-box. The kind of indicator shown in this figure is somewhat different from that already described (page 638), but the differences are only mechanical, the electrical principle being the same. In this case, when a current passes through one of the electro-magnets, owing to the circuit being closed at the corresponding "push," a little white card falls forward through a numbered or labelled slot in the front of the box, thus "indicating" which push has been used. The cards have to be replaced mechanically.

For purposes other than those just referred to, different methods of closing the circuit are employed. Thus, for fire alarms the rising of the mercury in a thermometer tube may, at a certain temperature, close the circuit and ring the alarm bell. The same object can be accomplished by the melting of a piece of fusible alloy releasing a spring, which then flies on to a contact point. For burglar alarms the contact is closed by the opening of windows or doors, and a switch is usually arranged so that all the circuits may be completely broken during the day-time; in that case the switch has to be altered at night, so as to bring the alarms into action should occasion arise. We regret that want of space precludes us from describing in detail some of the ingenious devices used for these and numerous other purposes, including electric time-keeping.

CHAPTER XIV.

THE ELECTRIC TRANSMISSION OF POWER.

We now turn to a wider aspect of the applications of the electric current, and one concerning which it is impossible to foresee at the present time all the consequences which may attend its development. In the three preceding chapters we have dealt with various applications of the current without much reference, except in the case of central stations for electric lighting, to the source from which the energy of the current was procured. In this chapter we propose to dwell in detail upon those properties of the current, already considered generally, which make it pre-eminently the vehicle for the transmission of power from convenient sources to far-distant points. It is true that the subject of the last chapter was a particular instance of such transmission, but in those applications the amount of power required and transmitted is so small that considerations of the sources from which it was obtained and of the loss in transmission are only of secondary importance. When, however, we face the problem of the transmission of power on a large scale, we find that, although the laws with which we have to deal are the same, some of the consequences of those laws, which before might be neglected because of their insignificance, now become of primary importance, and profoundly modify our methods and apparatus. This change of aspect is extremely interesting to the careful observer, and the description of the modifications it introduces into the treatment, and the solutions of the various new problems that arise, cannot fail to still further impress and familiarise the reader with the wonderful nature of the laws involved, and their far-reaching influence.

In dealing with this rather wide subject, we shall first consider the various systems available for the transmission, and the apparatus, not already described, peculiar to these systems. Having already considered the utilisation of the energy of the current at the distant end for lighting and chemical purposes, there still remains to show how it may be used to do mechanical work, and this, with a description of the various directions in which it has been so utilised, will conclude the chapter.

Systems of Transmission.

When, in a preceding[1] chapter, we were following out some of the consequences of the "law of conduction," we referred briefly to the methods in which the various conductors along which the current was to pass could be arranged. The two chief methods described were the "series" and the "parallel" (Figs. 157 and 158), and it was pointed out that combinations of these were also available. For "conductors" read "consumers of electric energy" in any form, and we have, in outline, two of the chief systems available for the electric transmission of power.

A distinction must here, however, be drawn between "long-distance transmission" and "local distribution" of the power at the place where it is to be utilised. Except in the case of electric railways and tramways, the power is, as a rule, required at perfectly definite points, and the details of the methods by which it is most conveniently distributed in the immediate neighbourhood of those points are governed by other considerations than those which rule the transmission of the power from a distance up to these points.

A little consideration will make it obvious that where a long distance intervenes between the source where the current is generated and the nearest point where the bulk of the energy is required, the simplest possible arrangement of conductors should be used. Of all methods, the simplest is that which involves only the use of two conductors, if the earth be not used as a return, to complete the necessary circuit, or, at the most three, as in the case of polyphase currents. Notwithstanding this, there still remains considerable choice as to the details of the transmission, as we shall now proceed to show.

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[1] Part II., Chap. VI.

In the chapter on "electrical measurements," when dealing with the measurement of power (page 408), we explained that, electrically, power is the product of two factors, the electric pressure or voltage, and the current or ampèrage. Thus, in a circuit in which 50 ampères are flowing under a pressure of 100 volts the power is 50 × 100 = 5,000 volt-ampères, or *watts*, as they are more briefly called. Therefore, if required to deliver power up to 120 kilowatts (120,000 watts, or 160 horse-power), at a distant point, we can choose the particular voltage and ampèrage which appears most suitable and economical.

Thus the 120 kilowatts may be given by any of the following combinations:—

A current of	10,000	ampères at a potential difference of	12	volts.
,,	1,200	,,	100	,,
,,	100	,,	1,200	,,
,,	10	,,	12,000	,,
,,	1	,,	120,000	,,

or any other combination of current and potential difference, provided always that the product of the number of ampères by the number of volts is 120,000.

We must, therefore, inquire what practical considerations there are to guide us in so wide a choice, and we soon find that, apart from side issues, there are two chief points to be kept in view. These are the cost of the power lost in wastefully heating the conductors or mains on the one hand, and the interest of the capital sunk in those mains, together with the cost of maintenance, on the other. Let us explain more fully. We already know that when a current passes along a conductor it heats it, and in the case with which we are dealing this heat is lost; but the heat so lost is *energy* which has been procured at some cost. In the first place, then, we should try to diminish this waste heat.

If we suppose the current in the conductors to be A ampères, R to be the resistance of the mains, E the potential difference at the generating end, and e that at the delivery end, then the heat, H, measured in *calories*, which is wasted in t seconds in the mains, is given by the equation (page 314)—

$$H = 0{\cdot}24\, A^2 R t \quad . \quad . \quad . \quad (1).$$

$$\text{Where } A = \frac{E - e}{R} \quad . \quad . \quad . \quad (2).$$

To reduce the amount of heat wasted in a given time we must, therefore, diminish either R or A, or both. R depends upon the *material* of which the conductor is made, its *length* and its *cross-sectional area.* As silver, the best conductor, is obviously too costly, the material usually employed is copper, which is nearly as good electrically. The *length* of the mains is fixed by the distance of transmission and the route available. We can, therefore, only still further reduce the waste by *increasing the cross-sectional area* or size and weight of the mains. But copper, though much cheaper than silver, is not inexpensive, and thus questions of finance very soon step in to complicate this solution of the difficulty. Moreover, the cost of manufacturing, insulating, and laying heavy conductors has to be considered. Although, therefore, increasing the size and weight of the mains is a theoretical solution of the difficulty, such increase cannot be extended indefinitely, for it soon reaches the limits allowable in practice.

Since these considerations of cost fix a limit to the reduction of **R**, we must turn to the other factor, **A** (the current), and examine the advantages and disadvantages of reducing it. It is at once apparent that any diminution of **A** is much more effective in reducing the waste of energy than a corresponding diminution of **R**, because the waste varies as the *square* of **A**, and is only directly proportional to **R**. Thus, a diminution of the current to $\frac{1}{3}$rd of its previous amount will reduce the waste energy to $\frac{1}{9}$th, if other conditions remain unchanged. To make this still clearer, we may take the example already given of the various currents that might be used to transmit a power of 120 kilowatts to a distance. We arrange the figures in a table :—

TABLE IX.—TRANSMISSION OF 120 KILOWATTS WITH VARIOUS CURRENTS.

Ampèrage (*Current in Ampères*).	**Relative Values of Waste Heat** (*Resistance constant*).	**Voltage** (*Pressure in Volts*).
10,000	100,000,000	12
1,200	1,440,000	100
100	10,000	1,200
10	100	12,000
1	1	120,000

A glance at the second column of this table will show how enormously the waste heat diminishes as the current is reduced, the waste heat in the first case cited being 100 million times that in the last. In actual practice the difference would not be quite so enormous, though it would still be very great, for no one would use the same conductors for a current of 10,000 ampères as for a current of one ampère. Smaller conductors would certainly be used in the latter case, and these, by their higher resistance, would somewhat increase the waste heat. In fact, one of the objects of using the small current is to enable us to save heavy expense in the conductors, and therefore to employ conductors of higher resistance. With the large figures disclosed by the table it is quite obvious that this object can be easily attained.

Since the diminution of the current has, then, such a great effect upon the energy wasted in the conductors, what is to prevent us reducing it still further, and far beyond the limits given in the table? The third column supplies an answer to this question. With the fall of the current there must be a corresponding rise in the voltage. This rise, if carried to extremes, introduces new difficulties. Electrically the chief difficulty is that of adequate *insulation.* It is obviously one of the conditions that the whole of the current that is sent out from the generating end of the line should reach the distant end where it is to be utilised. Any portion of the current which, owing to *leakage*, finds its way back to the generating source from any nearer point or points, represents so much energy wasted, just as the heat generated in the conductors represents wasted energy. Now the difficulty of efficiently insulating the conductors increases very rapidly with a rise of voltage, and at very high voltages it is doubtful whether any suitable material exists which will stand the enormous stresses and strains to which it must be subjected. At any rate, the *cost* of efficient insulation for high voltages is a factor whose importance increases much more rapidly than the voltage when we have passed a certain point. Practice has by no means said its last word as to where this point is, but up to the present a pressure of 30,000 volts[1] is the greatest that has been employed for actual heavy work. Moreover, it must be remembered that the voltages given in Table IX. are the voltages *at the distant end*, and are represented by e in equation (2). The voltage of the generating end, E, is necessarily still greater, for there must be some *volts lost* on the line.

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[1] In the *Lauffen-Frankfort Transmission* at the Frankfort Exhibition of 1891.

But there are still other considerations to be borne in mind. Conductors at high potentials are physiologically dangerous, especially if the high potential is being maintained by a machine with a vast reserve of energy, such as a large steam engine. Of course, they are only physiologically dangerous when, by any means, the living body is brought into conducting communication with them, and then the results may be disastrous, more particularly if the high potential be an alternating one. The effect in various cases we cannot here discuss. For our present purpose it will be sufficient to point out that the subject is so important that the Board of Trade, using the powers conferred upon it by Parliament, has issued bye-laws under which public supply companies are forbidden to place at the disposal of the ordinary consumer a P.D. greater than 300 volts.

Here, then, is a dilemma. On the one hand, long-distance transmission can only be economically accomplished at high pressures; and, on the other, only a comparatively low pressure is allowed to be handled by the consumer. How can these conflicting conditions be harmonised? Fortunately, there have been developed pieces of apparatus, both for continuous and fluctuating current systems, by which the voltage can be economically *transformed* from high to low, or *vice versâ*, at or near to the point at which the power is required. Such pieces of apparatus are most appropriately known as **transformers**; they will be described fully in the next section of this chapter.

We may now divide the various systems for the electric transmission of power, first of all, into *low-pressure* and *high-pressure* systems. From what we have already said, it will be obvious that the former is only available in cases where the consumer is close to the source of energy utilised, whereas the latter must always be employed where a considerable distance intervenes. Low-pressure systems employ continuous currents exclusively, and usually combine secondary batteries with the dynamos. High-pressure systems may use either continuous or fluctuating currents, though the latter only are used where the highest pressures are employed. As we have seen, suitable transformers are a necessary part of any high-pressure system for public supply. We may exhibit the various systems in a convenient form thus:—

TABLE X.—SYSTEMS FOR THE ELECTRIC TRANSMISSION OF POWER.

(A). **Low-Pressure Continuous Currents.**
  1. Simple parallel.
  2. Three-wire or five-wire.

(B). **High-Pressure.**
  1. *Continuous Currents.*
    (i.) Simple or multiple series without transformers.
    (ii.) Simple series or network with transformers.
      (*a*) Secondary battery transformers.
      (*b*) Motor-dynamo transformers.
      (*c*) Combinations of (*a*) and (*b*).
  2. *Alternate Currents.*
    (i.) Simple or multiple series without transformers.
    (ii.) Simple parallel or network with alternate-current transformers.
    (iii.) Simple parallel with transformer sub-stations supplying low-pressure network.
  3. *Polyphase Alternate Currents.*
    (i.) Three-wire transmission with transformers.

This list, though far from exhausting all the systems which are theoretically possible, includes most of those that have hitherto been adopted on any large scale in practice. We shall now briefly explain the chief details of these systems.

Low-pressure Systems.—The peculiarity of these systems is that they are well adapted for the distribution of electric power to a large number of individual consumers, placed close to one another in an area, no part of which is at a great distance from the source of supply.

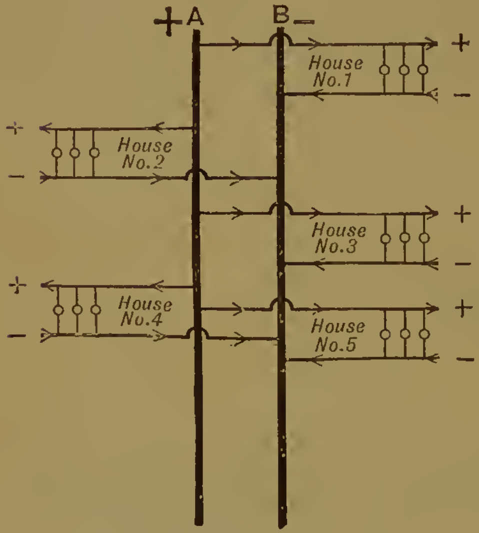

Fig. 334 – Two-wire Distributors.

The *simple parallel* system of distribution has already been diagrammatically illustrated and explained at Fig. 158, page 288. The method of connecting various consumers *in parallel* to public supply mains is also shown diagrammatically in Fig. 334, where A and B represent the positive (+) and negative (–) mains as laid down in the street, and the houses of the successive consumers are each supplied with two wires, one (+) joined to A, and the other (–) to B. Inside the house the lamps and other devices for utilising the electric energy are strung across these two wires or wires connected with them as shown.

In the *three-wire* system, as its name implies, three conducting mains are used instead of two. Of these one is the positive, and another the negative, conductor; whilst the third is at an intermediate potential, half-way between the first two. Each consumer is joined to this intermediate wire and one of the other two. The method of connection is diagrammatically depicted in Fig. 335. Here A is the positive (+), and C the negative (—) conductor, whilst B is the third wire, intermediate in potential between A and C. For instance, if the potential difference between A and C is 200 volts, that between A and B, or between B and C, is 100 volts. An examination of the diagram will show that consumers are joined to A and B, or B and C, but that no consumer is joined to A and C.

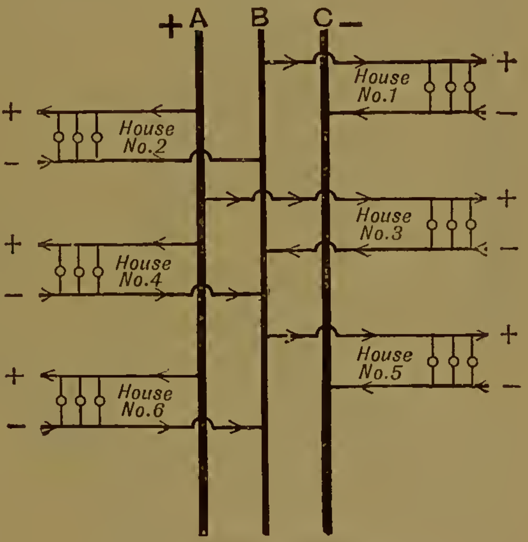

Fig. 335.—Three-wire Distributors.

The two- and three-wire connections that we have been describing are those of the consumers to what are known as the distributing mains, or more shortly the *distributors*. These mains may, and usually do, form a network, covering the whole district to which electric power is being supplied. They are maintained at a constant potential difference by another set of mains, which are usually referred to as the *feeders*, and which bring the current from the central or generating station, to selected points on them.

The connections between the central station, the feeders, and the distributors are diagrammatically shown in Fig. 336. Here A and B represent the positive and negative poles, as we may call them, of the central station. From these, pairs of conductors, represented by *thick* lines, are led away to selected points *a*, *b*, *c*, and *d*, of the network of distributors, which is represented by the *fine* lines. Wherever two of these fine lines run parallel and close together in the network, it will be found that one of them is in conducting communication

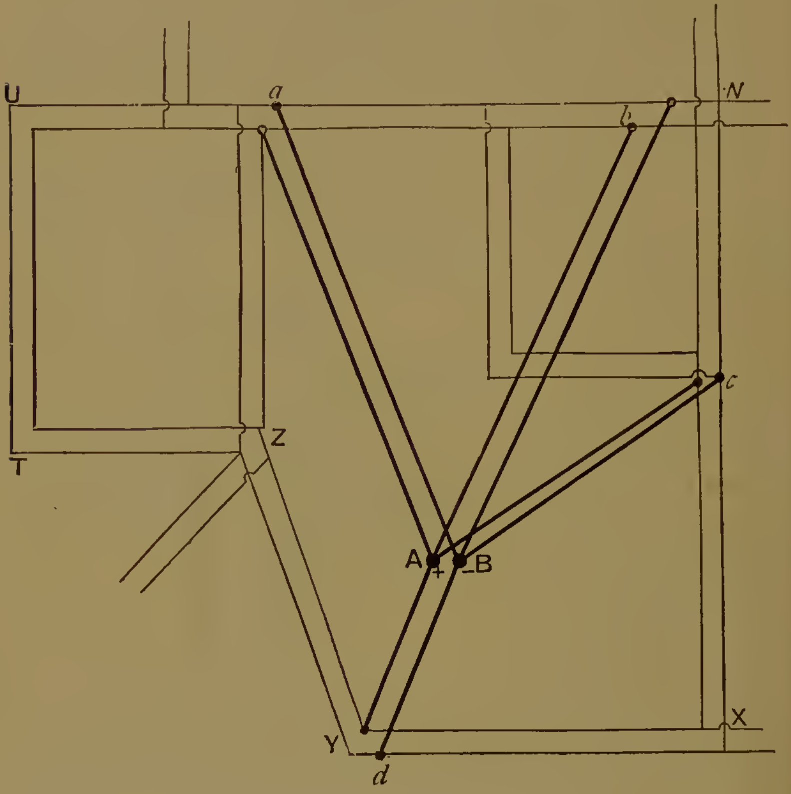

Fig. 336.—Feeders and Distributors.

with A, and the other with B. The duty of the central station is to keep the potential difference constant at every point of the network, and the points *a*, *b*, *c*, and *d* are to be so selected that, by keeping the pressure at them constant, the variations at the most distant parts of the network will be within certain small percentage limits.

In Fig. 336 the distributors, represented by the fine lines, are shown as consisting of two wires only; but the distributing network may be a three-wire system, the feeders in that case being connected to the mains, A and C, of Fig. 335. The advantage of using the three wires in the distributors is that the pressure between the feeders is thereby doubled, and for the same amount of power supplied only half the current flows through the feeders. The consequence is that the feeders may either be made of smaller cross-section and weight, or if they are kept of the same resistance only one-fourth of the heat-energy is wasted in them. The same remark applies to the distributors, for the outside mains, A and C (Fig. 335), can be made of less cross-section, having to carry only half the current. This saving, however, is partly counterbalanced by the necessity for laying the third wire, B (Fig. 335). On the whole, the three-wire system leads to a substantial saving, both in the first cost of the feeders and distributors, and also in the energy dissipated as heat in the conductors.

The *five-wire* system is an extension of the three-wire one. In it the distributors consist of a network of five wires, two of which are maintained at a constant potential difference by the feeders, and the remaining three are at intermediate potentials. The connections of an actual system of this kind, as used in Paris, are shown in Fig. 337, where O is the position of the central station, from which pairs of feeders are led to the points M, N, P, Q, and R of the distributing network. This network consists of the series of five parallel lines, forming the figure A, B, C, D, E, with cross connections B E and B D. The feeders maintain the outer wires at a potential difference of 440 volts, and the regulating arrangements are such that the pressure between any pair of contiguous wires is one-quarter of this, namely, 110 volts. The regulating devices consist of secondary batteries, shown at *f*, and a special form of motor-dynamo, shown at *g*. Although only single cells are shown at *f*, it must be understood that each of these is intended to represent a 110-volt battery of 53 or more cells, the number of cells being automatically changed as required. The

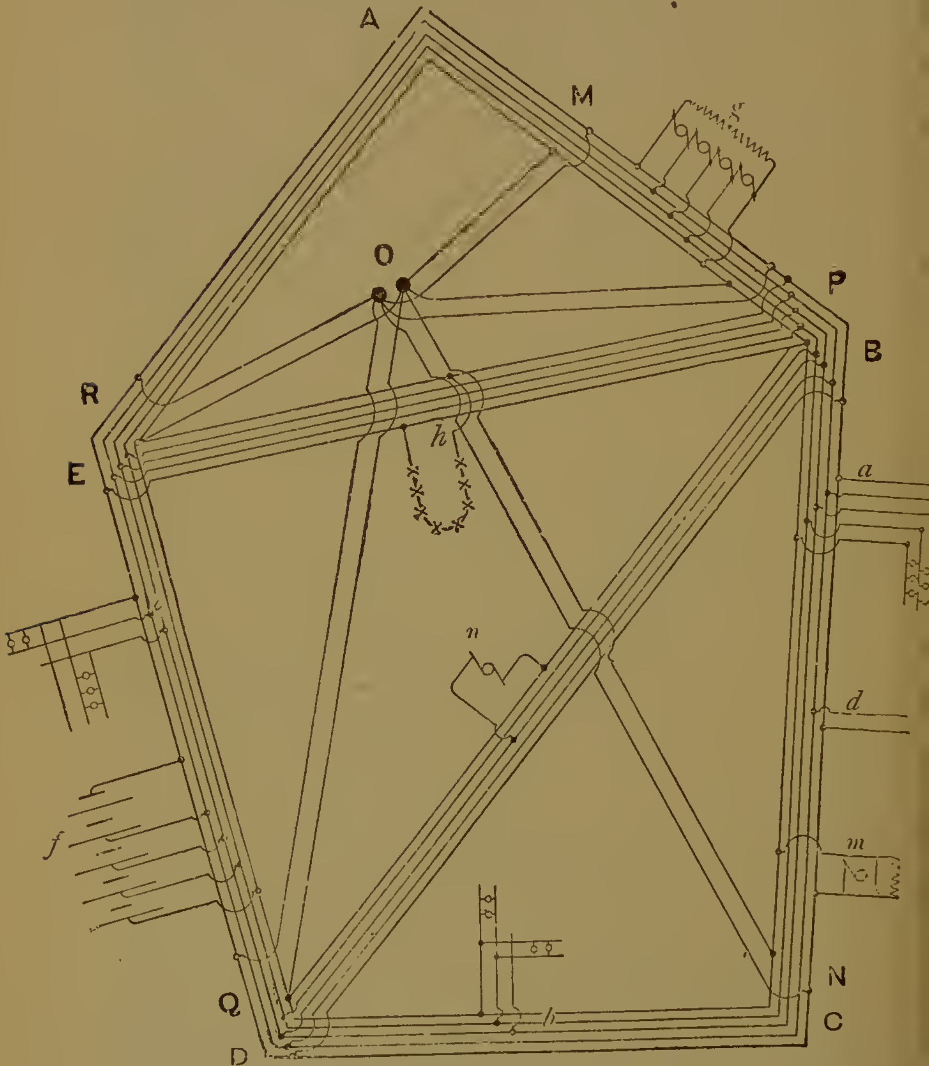

Fig. 337. -Connections of a Five-wire System.

motor-dynamo at *g* will be explained in the next section. The little circles on the side lines at *a*, *b*, *c*, and *d* represent 110-volt glow lamps on consumers' premises, whilst at *n* a 220-volt motor bridges two sections of the system, and at *m* a 440-volt motor is joined to the extreme conductors. Lastly, at *h* eight arc lamps in series are shown as taking the requisite current at 440 volts from the two external conductors.

The advantage of the five-wire system is that it leads to a still greater saving of copper as compared with the three-wire system, whilst its great disadvantage is the difficulty of efficiently regulating the potential of the three intermediate wires. Both the three- and five-wire systems are, as compared with the simple-parallel system, steps in the direction of high-pressure distribution, and, for the reasons already given, render possible the economical transmission of the electric power to still greater distances from the central station.

High-pressure Systems.—In Table X. the first two main divisions of these systems distinguish between continuous and alternate currents; but the first sub-division in each of these is the same, namely—"simple, or multiple series, without transformers." We may therefore take these together.

The *simple-series* system of arranging conductors, which has been already explained at page 287, is confined almost exclusively to the arc-lighting of streets and large public places, such as railway stations, markets, etc. The lamps, which utilise the power, are strung one after the other on the mains, and have automatic devices for shunting the current past, if by any accident the lamp ceases to burn.

The *multiple-series* system is suitable, and is used chiefly for running groups of glow lamps in series with arc lamps, and is, therefore, useful for lighting streets, railway stations, large shops and public enclosures. There are many possible arrangements. For instance, a current maintained always constant at, say, 10 ampères can be supplied to a long circuit in which a number of arc lamps are inserted in series. But if glow lamps are required at any point, eight of these, connected in parallel, can be inserted to replace a single arc and distributed as required. Should one of the glow lamps in any group of eight break, the remaining seven would have to take the whole current, which would probably soon destroy them. To prevent this an equivalent wire resistance is put at the top of each lamp, which is automatically switched into circuit if the lamp breaks, and thus takes the current until such time as the lamp is replaced. Other devices, which we need not here describe, are also used for the same purpose.

Continuous-current systems.--Passing now to the purely continuous-current systems, the second subdivision of Table X. specifies a "simple series or network with transformers." The transformers proper to a continuous-current system are further referred to as either "secondary batteries" or "motor dynamos." The first of these has already been fully described at pages 77 to 86, and the motor-dynamos will be described in the next section of this chapter. We are here concerned rather with the methods of using these. The general way of carrying out the principles involved will be best understood from the description of a particular application. For this purpose we select the system used by the Chelsea Electricity Supply Company, which is shown diagrammatically in Fig. 338. In this diagram, the three dynamos, D D D, connected in series, supply current to the mains, *m m*, at a pressure of 500 volts. These three dynamos may, of course, be replaced by a single dynamo generating a current at this pressure, but when not used for the purpose here described, these particular dynamos can be employed, in parallel, to feed an ordinary low-pressure network of distributors. The battery and motor dynamo room may be at some distance from the central station, and is in the centre of the district to be supplied. The

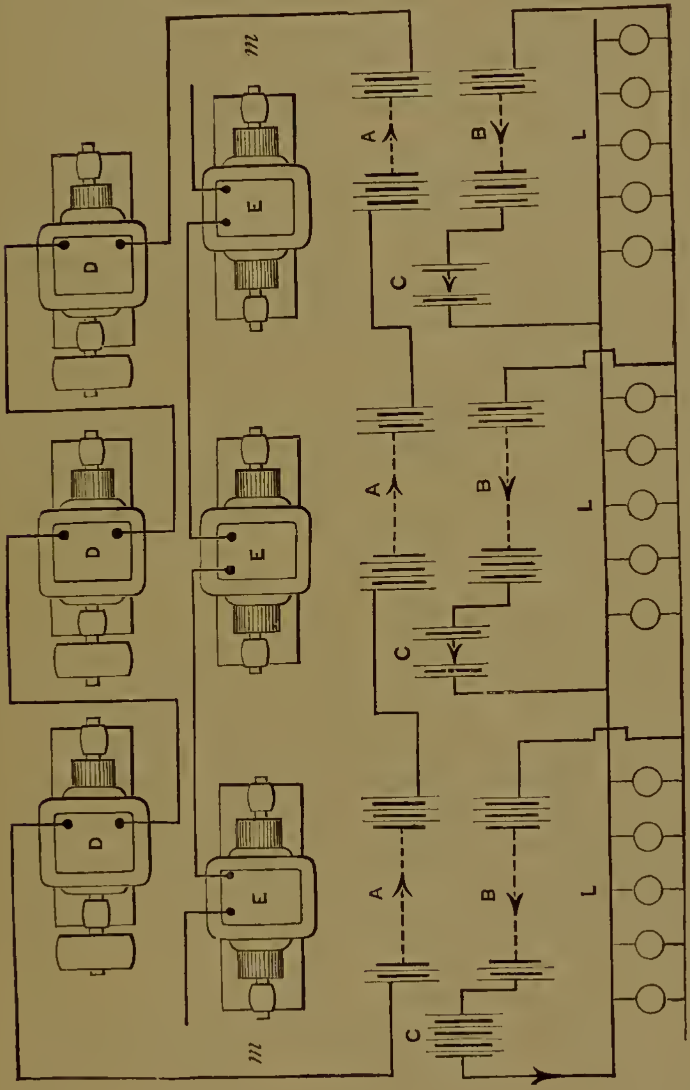

Fig. 338.—Secondary Batteries as Continuous-current Transformers.

secondary battery consists of two halves, A and B, each subdivided into four sections consisting of 54 cells each;

of these sections, only six, three for each half, are shown in the figure. The general idea is to charge only one-half of the battery at once, and to *always* have at least one-half discharging into the distributing network, L L L, which might be either a two-wire or three-wire network, but in this case is a two-wire one. In the figure, the half-battery A is shown with its various sections joined up in series and connected to the charging mains, *m m*. The other half, B, has its sections arranged in parallel and connected to the distributors, L L L. When A is fully charged, it is to be automatically disconnected from the charging mains, its various sections put in parallel, and then connected to the distributing network.

When either section, A or B, is discharged, it is automatically taken off the distributors, joined up in series, and placed on the charging mains, *m m*. The cells, C C C, in the discharging half, B, are reversed cells, by the automatic cutting out of which the P.D. of the whole section concerned is kept at 100 volts.

As soon as both sections are fully charged and placed on the distributors, the engines can be stopped and the cells left to do their work. But during the hours of heaviest demand the load on the cells exceeds their capacity: when this time arrives, the dynamos are again started, and the mains, *m m*, connected to the primary circuits of the motor-dynamos, E E E, from whose secondary circuits, as will be presently described, currents at a pressure of 100 volts are fed into the distributors to help the battery. The complete system is, therefore, an example of sub-section (*c*) of Table X.

The whole of the rather complicated changes referred to above are made by a series of mercury switches automatically actuated by some exceedingly ingenious apparatus devised by Mr. F. King; this apparatus, however, is much too technical in its nature for us to describe here.

Alternate-current systems.—In by far the most important high-pressure transmissions of power alternate currents are used. In fact, it is their adaptability to this work that has led to the very rapid development of their application in practice, for with them very much higher pressures can be used than have yet been found possible with continuous currents, and thus the economy due to high pressures becomes more pronounced. This is more especially the case where the source of energy is at a great distance from the place where it is desirable to utilise it.

We have already sufficiently described the first method of Alternate-Current high-pressure transmission, referred to in Table X. With regard to the second method, which contains the most widely-used systems, the diagram already given in Fig. 336, of feeders and distributors, sufficiently well depicts the general arrangement of the high-pressure part of the system. The only difference is that neither A nor B can now be called the positive or negative terminal of the station, since each is alternately positive and negative. Another difference in practice will be that the method of laying and insulating the distributing mains and feeders will be altogether changed. Last, but not least, the consumers, instead of being directly connected to the distributors, are connected to them through induction coils or alternate-current transformers. The primary terminals of the induction coils are permanently joined to the mains, and covered up so as to be inaccessible to the consumer, who is, instead, supplied with two wires coming from the secondary terminals of the coil. As the electric pressure on these wires seldom exceeds 100 volts, and sometimes is only 50, they can be handled with comparative safety.

It will be noticed that whether the consumer is using energy or not, the primary circuit of his transformer is always connected up to the mains, and, therefore, some current must always be passing through it. This leads to a waste of energy which may become serious when continued throughout the twenty-four hours and all the year round. To meet this difficulty, the next system tabulated has been devised, and is becoming widely used.

In the last alternate-current method referred to in the table, the transformers, instead of being placed on the consumer's premises, are placed in a sub-station in the centre of a small district, throughout which low-pressure distributors are laid.

In this sub-station the transformers are "banked," as it is called—that is, there are several transformers with their primaries and secondaries in parallel. As the load on the secondaries increases, more transformers are switched into circuit, and the idea is to work every one in circuit as nearly as possible at full load, that is, under the conditions of greatest efficiency. The regulation of these "banked" transformers at first proved somewhat troublesome, but the difficulties are now being overcome.

A unique method is used by the London Electricity Supply Corporation. At the large station at Deptford an alternate current is delivered to the transmitting mains at a pressure of 10,000 volts. This high-pressure current is taken to various sub-stations at Charing Cross and other convenient places in London, where it is transformed down to larger currents at a pressure of 2,400 volts. These currents are fed into high-pressure mains in the immediate neighbourhood of the sub-station. The consumers are connected to these mains in the way already described, through transformers, which still further reduce the pressure to 100 volts. In this way, some of the energy is finally used at a distance of 9½ miles from the engines and dynamos at Deptford.

Polyphase Transmission.—The remarks we have already made (see pages 458 to 462) on polyphase alternate-currents leave us little to say on this subject, for we propose to deal with the motors separately. In the Frankfort experiments the transmitting wires were ordinary copper telegraph wires, 0·158 inch in diameter, carried in the usual way on poles with oil insulators. There were, since three-phase currents were used, three wires instead of two, and with these thin wires as much as 81 horse-power was transmitted a distance of 110 miles, the pressures used being sometimes as high as 30,000 volts.

MAINS AND CONDUCTORS.

In the foregoing we have simply explained, with the aid of diagrammatic figures only, some of the chief systems at present in use for the electric transmission of power. We have purposely abstained from formulating or discussing any rules for calculating the proper size of conductor to be used in any given case, or from referring to the many details connected with the laying and insulating of the conductors.

The various systems that have been invented for the latter purpose are very numerous, and an attempt even to classify them would be wearisome to our readers. Still, some brief reference may be interesting, and we therefore select for description two as far apart as possible, one for low- and the other for high-pressure mains.

It should perhaps be premised that, except in one or two cases where very high pressures are used, the electric transmission of any considerable amount of power requires such heavy conductors that it is almost impossible to mechanically carry them on poles like telegraph wires. Also, since such poles and conductors in the main streets of a town are very unsightly, they frequently are tabooed, even where they are possible from an engineering point of view. The two systems described are, therefore, both underground systems.

As a good example of a system of low-pressure mains for a three-wire distribution, we select that used by the St. James's and Pall Mall Electric Light Company. Here the mains are laid in iron culverts of the shape shown in Figs. 339 and 340. The culvert is made in lengths of three feet six inches, and consists of two parts, the lower one being a kind of trough, and the upper one a lid or cover. The former is ten inches wide and six inches deep. At intervals, glazed earthenware insulators, to support the conductors, are laid in the trough, and on these the three sets of conductors rest without any insulating covering. The conductors consist of thin copper strips set on edge, each strip being 2 inches wide and 0·1 inch thick. A sufficient number of strips are used to carry the current to be transmitted, and it will be noticed that the central conductor contains fewer strips than the outer ones.

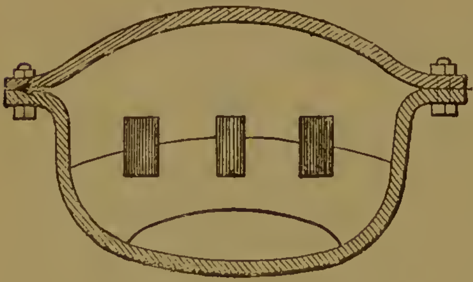

Fig. 339.—Iron Culvert for Bare Copper Mains.

As the conductors are bare, it is very essential that the culvert should be kept quite free from moisture. To ensure this, the cover is firmly bolted on to the lower trough, and all joints made water-tight. Moreover, junction-boxes, or manholes, which are also required for testing and other purposes, are placed at intervals, and the culverts are sloped towards them, so that any water

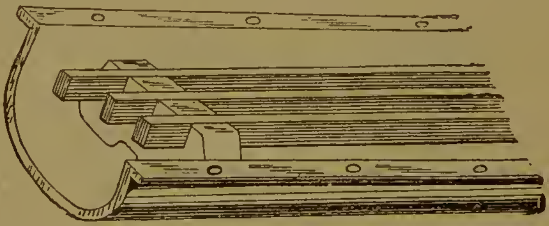

Fig. 340.—Section of Iron Culvert.

that might collect, drains into the nearest junction box. These boxes are built of brick and lined with cement, and the culvert projects into them at some little distance from the bottom. They are usually connected to the nearest drain. Ordinary copper cable, insulated with vulcanised rubber, is used to connect the consumers on either side to the mains. It is laid in gas-piping to protect it from mechanical injury.

The other example of underground main is that used by the London Electric Supply Corporation for the high-pressure (10,000 volts) alternate current from the Deptford station. A full-size cross-section of this cable, as designed by Mr. Ferranti, is represented in Fig. 341. The two conductors are concentric cylinders, one inside the other. The inner conductor is a hollow cylinder $\frac{1}{4}$ inch thick, and with an outer diameter of $\frac{13}{16}$ inch. This is overwound with layer after layer of brown paper soaked in black mineral

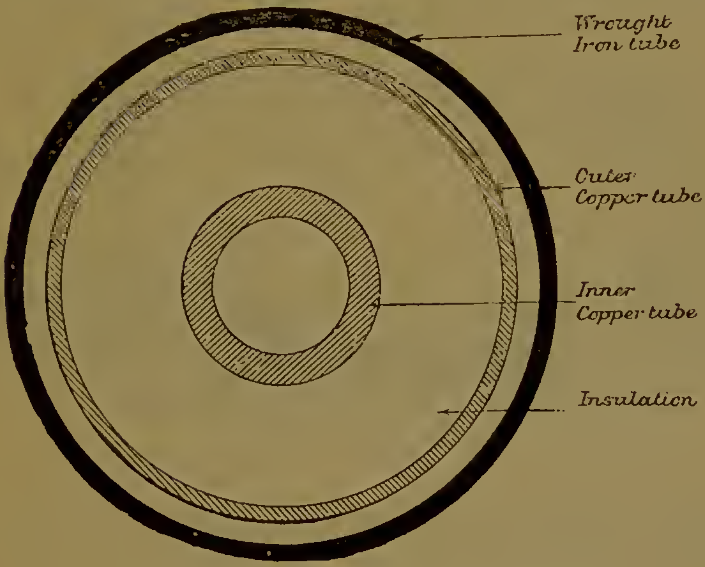

Fig. 341.—Section of Ferranti Trunk Main (full size).

wax or ozokerit, which when carefully prepared is found to have high insulating properties. The right thickness of insulating material having been wound on, the outer cylindric conductor is slipped over it and the whole drawn through a taper die, which compresses the conductor firmly and tightly on the brown paper. When finished, this outer conductor is $\frac{3}{32}$ inch thick, and has an outer diameter of $1\frac{15}{16}$ inch. Another $\frac{1}{8}$ inch of waxed paper is wound on outside the copper tube, and then a thin wrought-iron tube is slipped over this, and the interspace filled with melted wax.

The compound conductor is made in lengths of 20 feet, which are afterwards carefully joined and laid on wooden bearers in wooden troughs, which are then filled with pitch and covered over. At intervals test boxes are placed, by means of which convenient lengths of the main can be isolated for testing purposes. One of these is shown, in section, in Fig. 342. The mains enter the box from each side through stuffing boxes, D D. The inner conductors project beyond the insulation, which in the figure is indicated by dark shading. They are then connected by crank pins and the bolt A. A much longer and well-insulated clamp connects the outer conductors. When not being

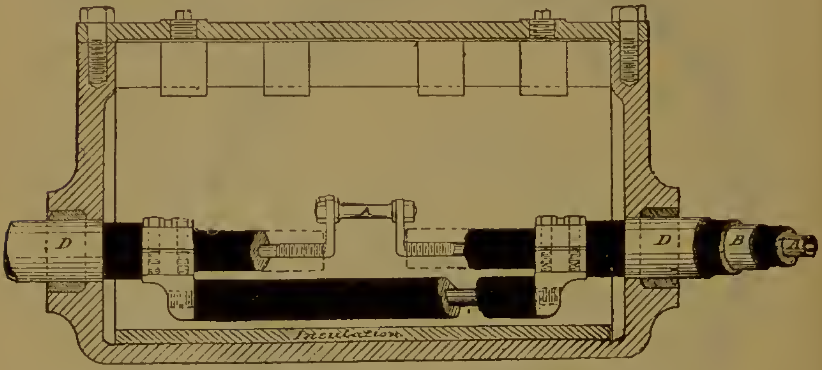

Fig. 342.—Test Box on Ferranti Main.

used for testing purposes, the box is covered up with a tightly-fitting cover, and, pumped full of heavy resin oil, which itself is a good insulator.

Transformers.

In the preceding section we have shown that the economical transmission of power to a distance by means of the electric current is only possible when comparatively high pressures are used, the economical pressures being much beyond the limits which it is safe for the ordinary consumer to employ. We have also pointed out that the high-pressure transmission is made available by the fact that there are methods by which, *at the distant end of the line*, the energy can be *transformed* from high-pressure to low-pressure electric energy, which latter can then be supplied to the general public. These methods involve the use of pieces of apparatus which are most appropriately termed **Transformers**, though other names have been proposed. In this section we propose to describe the different systems, and the apparatus appropriate to each.

Let us first, however, for a moment consider the general problem. We have already seen[1] that the energy expended in a part of a circuit conveying a current of **A** ampères, at a P.D. of **V** volts, for **t** seconds is expressed by the equation

$$\textbf{Energy in joules}^{2} = \mathbf{A} \times \mathbf{V} \times \mathbf{t},$$

and we have more than once pointed out, that, for the same total amount of energy, the values of **A**, **V**, and **t** may be varied through wide limits. The object of a transformer is to change the values of these quantities without changing the total amount of energy, and in the ideally perfect transformer the change would therefore be so made that

$$\mathbf{A} \times \mathbf{V} \times \mathbf{t} = \mathbf{A}' \times \mathbf{V}' \times \mathbf{t}',$$

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[1] Page 413, *et seq.*

[2] One *joule* = 0·74 *foot-lb.*

where the symbols on the right-hand side represent the new values of the quantities after transformation. It may at once be said that no such perfect transformer exists, and that, in practice, the value of the product on the right-hand side (*i.e.*, *after* transformation) is always less than that on the left-hand side, owing to the dissipation of energy by effects which may, in a general way, be regarded as frictional.

Taking, then, the last equation as representing that perfection which it is the object of all to attain, we may examine in detail the various quantities involved. Dealing first with the times $\mathbf{t}$ and $\mathbf{t}'$, we may remark that unless the transformer can *store* the energy ($\mathbf{A} \times \mathbf{V} \times \mathbf{t}$) as received by it, and deliver it for use when afterwards required, these two symbols must express the same period of time. In other words, if there is no *storage* of energy, it must be used during the time of transformation. The only practical system of transformation which permits the storage of the energy is that which uses **Secondary Batteries** as transformers. In this system, which, it is obvious, can only be used with *continuous currents*, the batteries are arranged to be charged at a high voltage at the most convenient rate and time, and, then, being re-arranged, can be discharged at a lower voltage, either slowly, or at any desired rate up to the maximum beyond which it is not advisable, because of the rapid deterioration of the plates by buckling, etc., to take energy from them.

In the other two systems of transformation that have been practically worked out, the energy is delivered into the supply mains, and must be utilised as it is transformed. In these systems, therefore, $\mathbf{t}=\mathbf{t}'$, and our previous equation reduces to

$$\mathbf{A} \times \mathbf{V} = \mathbf{A}' \times \mathbf{V}'.$$

These systems, thus, only permit us to transform from a high P.D. (**V**) and a small current (**A**), to a lower P.D. (**V**′) and correspondingly large current (**A**′); the product of P.D. by current in the second case being as nearly as possible, but never equal to the product of P.D. by current in the first case. Of these systems one which employs **Motor Dynamos** as transformers is applicable to *continuous currents*, whilst the other, which uses *induction coils*, or **Alternate-Current Transformers**, is, as the latter name implies, only applicable to *alternate* or *fluctuating currents.* In what follows, it will be most convenient to treat continuous- and alternate-current transformers separately.

CONTINUOUS-CURRENT TRANSFORMERS.

Secondary Batteries.—In the first section of the book (pages 66 to 89) we have described the principles and the construction of secondary batteries, and it is therefore only necessary to refer our readers to what we have there said, and especially to the descriptions of "Central Station Cells," which are most useful as transformers, because of their large storage capacity.

The method of using secondary batteries as transformers has also been described (page 664) in connection with "Systems of Distribution." It will be noticed that the essential point is to *charge* several complete batteries *in series*, and to *discharge* them *in parallel.* Thus the high voltage and small current of the charging mains is transformed into a lower voltage, and, if required, a larger current in the discharging mains. With secondary batteries, however, the discharging current need not necessarily be greater than the charging current, but may be continued for a much longer time. The example already given is sufficient for our purpose, and we therefore pass on to consider the second method of continuous-current transformation.

Motor Dynamos.—These appliances for the transformation of the energy of one current at a certain voltage into the energy of another at a higher or lower voltage are variously known as "Motor Dynamos," "Motor Generators," "Dynamotors," and "Continuous-Current Transformers." Of these different names we prefer the first, though perhaps the second is best from a strictly scientific point of view.

The general principle underlying the action of the machines is a simple one. As we show on page 696, an ordinary continuous-current dynamo is a reversible machine, and when supplied with electric-current energy, will do mechanical work, such as a steam or a gas engine can do. When used in this way it is known as an Electric Motor, or, more briefly, a "Motor." Now, it is quite obvious that amongst the various kinds of work such a motor can do, it may be used to drive a dynamo, and so reproduce electric-current energy. But the dynamo so driven may generate a current at a very different voltage to that supplied to the motor, and therefore, finally, we obtain a new current at a different voltage to that of the old current with which we started.

The general law, already explained, applies to this case also, and in the most favourable circumstances we might have

$$\mathbf{A} \times \mathbf{V} = \mathbf{A}' \times \mathbf{V}'.$$

But there is a double transformation involved, first from electric to mechanical energy, and then back again to electric energy, and therefore we never get $\mathbf{A}' \times \mathbf{V}'$, the watts after transformation, equal to $\mathbf{A} \times \mathbf{V}$, the watts before transformation.

Simplifications in the general arrangement of the apparatus are obviously possible. Instead of driving the dynamo from the motor by means of a belt, the two shafts might be placed in line and coupled together, only in this case they must both be designed to run at the same speed.

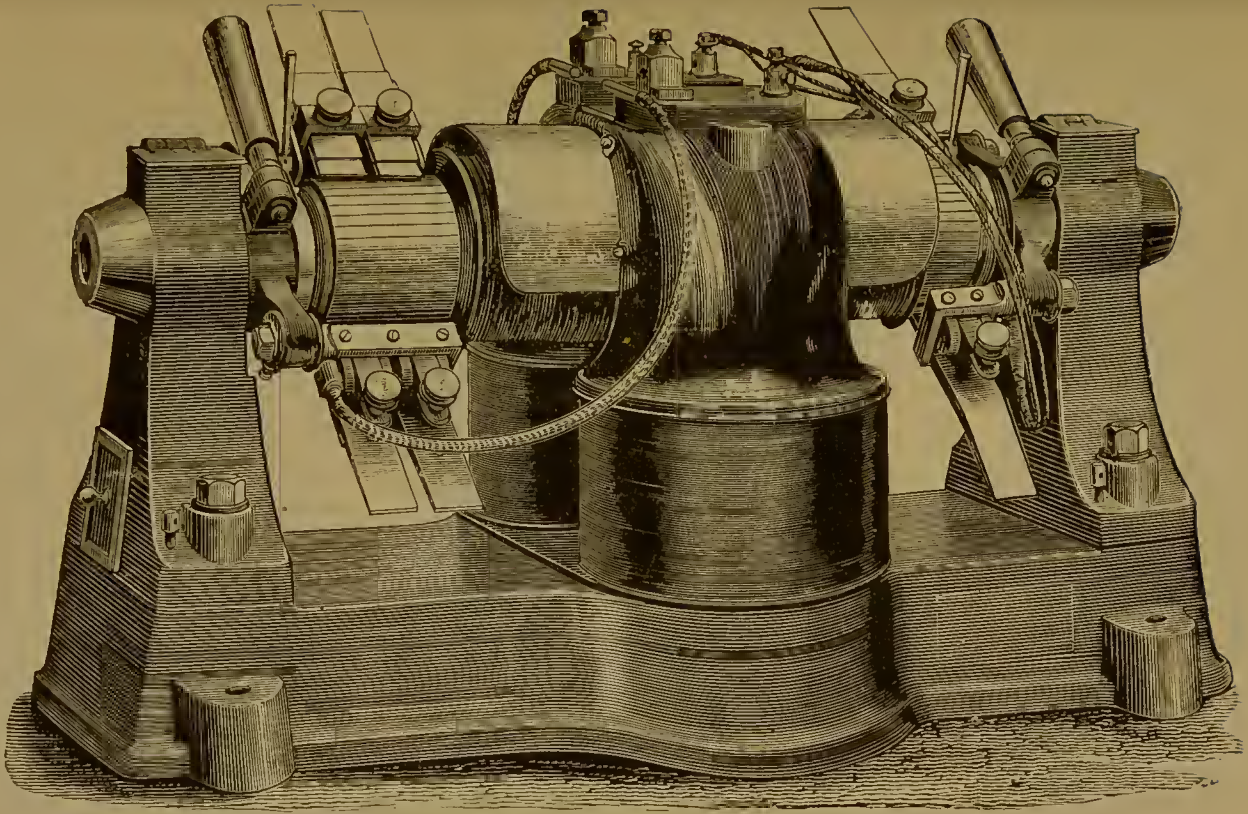

FIG. 343.—NORWICH MOTOR-DYNAMO.

Still further, instead of *two armatures* on the same shaft, rotating in *two magnetic fields*, one of the fields might be lengthened, and both armatures rotate in different parts of the same field. Finally, the two armatures might also be replaced by one armature with two sets of windings lying side by side, and connected to two separate commutators.

The last is the form now usually given to the machine, though some engineers still advocate keeping the two machines, the motor and the dynamo, quite distinct, with only a mechanical connection, such as a belt or a coupling, between them. A combined machine, as made by Messrs. Laurence, Scott & Co., of Norwich, is shown in Fig. 343. It differs in appearance from a dynamo only in the absence of a driving pulley, and in having two commutators, one at each end of the armature. In this case the motor-dynamo is intended to transform "down" from 100 volts to 20 volts, and the field-magnets are excited by a shunt circuit in parallel with the high-pressure brushes on the right-hand commutator. The current, then, drawn from the left-hand commutator, will be greater in volume, but diminished in pressure, as compared with the current supplied to the other commutator. As the shaft of the machine runs at a fairly high speed, it is necessary to have self-lubricating devices, which will enable it to run for a long time without attention.

If a pulley were fixed on the shaft of the machine, it would have a wider range of possible use. For instance, when driven by some mechanical source of power, it can be used to generate two distinct currents. Or, if supplied with electric power, it can be used, not only to generate another current, but also as a source itself of mechanical power.

We shall conclude by describing the motor-dynamo, which is used as a regulator on the five-wire system, referred to on page 661. In this system it will be remembered that there are four different circuits from which current may be supplied to consumers, and that it is necessary to have the same pressure on each circuit, however the demand may vary from time to time. As one method of regulating the pressure, the motor-dynamo shown in Fig. 344 is used. In this machine the armature is wound with no less than *four* distinct circuits, lying alongside of one another, and connected to four separate commutators, two at each end. The circuits are exactly similar, and similarly placed on the armature; they are connected respectively to the four circuits of the five-wire system, and are therefore in series with one another. The field-magnets, which in this case are of the "double-magnetic circuit" type, are excited by a current maintained by the full P.D. (480 volts) of the system.

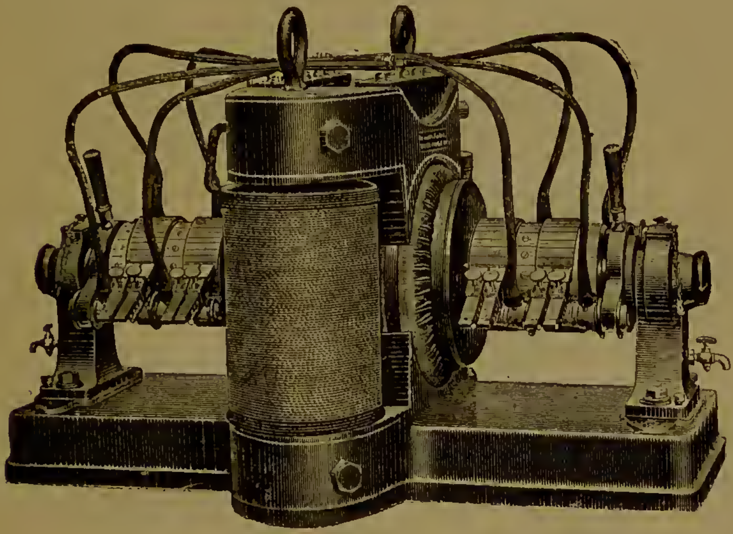

Fig. 344.—Quadruple Circuit Motor-Dynamo.

The action of the regulator is simple. If all the sections are at the same pressure, a small current flows through all the armature circuits, and the armature rotates at a moderate speed. Should, however, the pressure of one section increase at the expense of the others, the armature circuit connected with that section receives an excess of current, and the armature rotates more quickly. This increases the E.M.F.'s set up in the other three armature circuits, and these E.M.F.'s, having a diminished pressure against them on the mains, act as dynamo E.M.F.'s, and drive currents into the mains. Thus, the increased pressure on the one section is lowered by the current drained away from it to the corresponding armature circuit, whilst the lowered pressure on the other sections is raised by the currents supplied to them. To some extent, therefore, the machine automatically regulates the pressure.

Alternate-current Transformers.

The fundamental phenomena underlying the working of alternate-current transformers have been already very fully discussed, at page 169, *et seq.*, in connection with the subject of "Magneto-Electric Induction," and, as we have there shown, these phenomena form the starting-point from which the modern dynamo machine has been developed. At page 170 we have described the first such transformer ever made, consisting simply of two spirals wound side by side on a block of wood. This was afterwards improved by the construction of the iron ring, A B, Fig. 89, with two separate coils of wire on it. This ring of Faraday's we reproduce here (Fig. 345) on a larger scale, as the forerunner of a class of transformers to which we shall refer more fully later on. As we now know, the starting or stopping of a current in the coil A produces a momentary electric pressure in coil B, and also, any change of current in A produces a momentary pressure in B, which persists as long as any change is taking place in A.

What, then, will happen if the coil A be traversed by such alternate currents as we have been describing at page 426 and elsewhere. The distinctive character of these currents is that they are continually changing—sometimes increasing, sometimes decreasing, but never retaining the same value for any appreciable time. It is obvious that in this case an alternate E.M.F. will be set up in the coil B; this E.M.F. will follow the same kind of changes as the *self-induction E.M.F.* of the coil A itself, and may be represented by a curve similar to *e e e* of Fig. 217. For brevity, the coil A, through which currents are sent by some external E.M.F., is now usually referred to as the *primary* coil, whilst coil B, which is traversed by *induced* currents only, is referred to as the *secondary* coil.

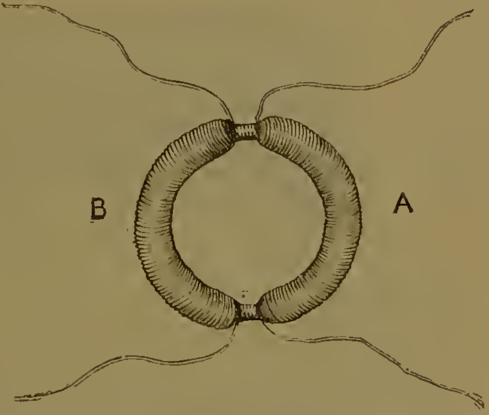

Fig. 345.—Faraday's First Transformer, with Iron Core.

Almost simultaneously with Faraday, and quite independently, Henry was making in America the experiments on the mutual inductive effects of flat spirals, to which we have briefly alluded at page 182. Faraday's and Henry's experiments together form the starting-point of the work of a long series of scientists and inventors, who, by various modifications and rearrangements of the positions of the two coils, and other subsidiary improvements, have endeavoured to utilise the E.M.F. set up in the secondary coil, B, for some particular kind of electrical work. These essays reach from 1831 to the present day, but down to about 1877 they were mostly directed to the setting up of a very high E.M.F. in the secondary coil, available for the production of disruptive electrical discharges between its terminals. Such "induction coils," as they are usually called, can be used for many interesting and instructive experiments with very simple auxiliary apparatus. We shall therefore describe one of the latest forms, without taking our readers through the long story of their gradual development.

Fig. 346 shows the external appearance of a good modern induction coil as made by Mr. Apps, who has done much to improve many of the details. The working of the coil will perhaps, however, be best understood from Fig. 347, which is a diagrammatic sketch of the electrical connections. Round an iron core, T T, of varnished soft iron wires, and well insulated from it, is wound the primary coil, P P, consisting of two or three layers, each containing a few turns of stout copper wire, sometimes of square section, so as to fill the space more completely. Over this coil is slipped an ebonite tube (not shown in Fig. 347), which projects some distance beyond the secondary coils, which are wound

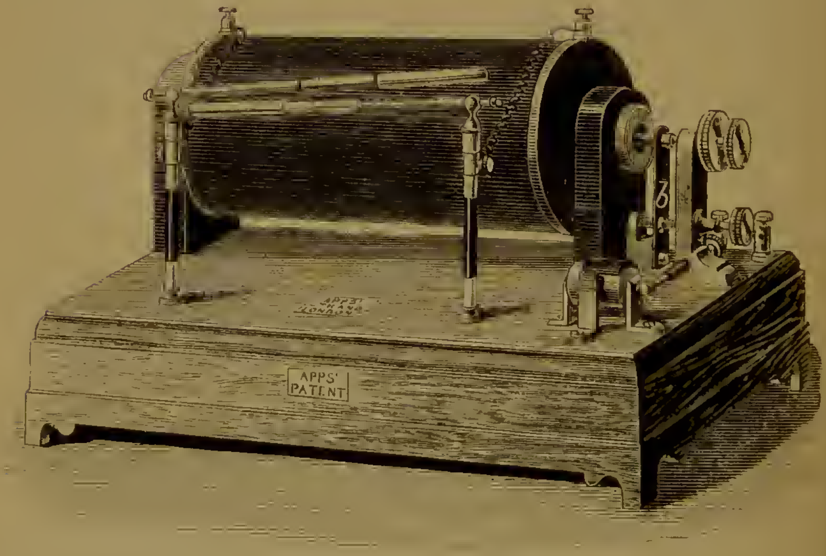

Fig. 346.—Battery-Current Induction Coil.

outside it. On this tube are threaded a number of discs of ebonite, separated by narrow rings, which act as distance pieces. The secondary coil, S S, is wound in sections of flat spirals, which fill the spaces between successive discs, and are ultimately connected together in series. The object of thus splitting up the secondary coil into many sections is to ensure that no two portions of wire, which will be at very different potentials when the coil is worked, shall be close together in the windings. The ends of the secondary coil are brought, by means of the thin wire spirals, to the terminals, *t t*, which are supported by glass insulating pillars. The terminals carry, by ball-and-socket joints, the discharging rods, *r r*, which are provided with ebonite handles.

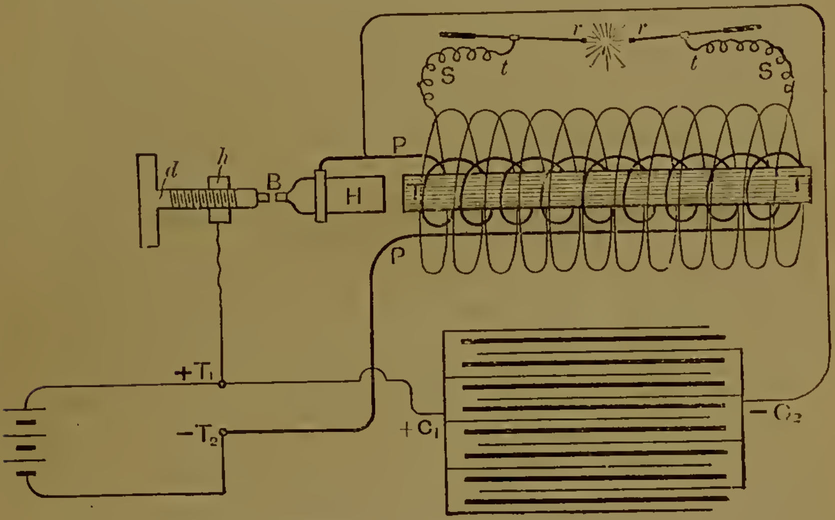

Fig. 347.—Connections of a Battery Induction Coil.

The electrical connections of the primary windings are somewhat more complicated. Since, during the development of the induction coil, alternate currents produced by dynamo alternators were not available, some means had to be provided on the coil itself for producing the necessary variations (usually interruptions) in the steady current generated by primary batteries. Very numerous inventions were directed to the improvement of this part of the coil; but, eventually, the very simple arrangement shown in the figures has survived. The laminated iron core, T T, is made to project some little distance through the supports of the coil. Opposite to the end of it is a piece of solid iron, H (Fig. 347), carried by a stout spring, *b* (Fig. 346), which can be so set up by the adjusting screws shown that when no current is passing through the circuit P P, a platinum contact at B, behind H, rests against another platinum contact on the end of the screw *d*. One terminal, T_1, of the coil is connected to the nut *h*, through which the screw *d* passes, and the other terminal, T_2, to one end of the primary coil P P, the other end of which is joined to the spring *b*, which carries the hammer H. If now the poles of a galvanic battery be joined to the terminals, T_1 T_2, the current must pass through the platinum contacts at B. But as soon as the current passes, the core T T is magnetised and attracts H, thus breaking the circuit of the battery at B; consequently, the current in the coils P P dies away, the magnetism of T T disappears, and the elasticity of the spring *b* brings the platinum contacts at B together. The current, therefore, again flows from the battery, is again broken, again made, and so on, continuously.

The result is that a series of interrupted currents, all in one direction, flow through the coil P P; each current starts from zero, rises to a maximum, and then falls off to zero again. As the self-induction of P P is large, these currents, for reasons already given (page 427), do not instantaneously reach their maximum on making circuit, nor do they instantaneously fall to zero when the circuit is broken.

But whether the current in P P rises and falls quickly or slowly, its changes will induce E.M.F.'s in each coil of S S, and as these coils are very numerous and in series, the effective E.M.F. set up, and with it the P.D. of the terminals S S, may reach a very high value. So high may this P.D. rise, that the insulating air separating the terminals may be disruptively broken, and a series of brilliant sparks pass between the knobs.

We have still to explain the action of the piece of apparatus represented by C_1 C_2 in Fig. 347, and which is usually enclosed in the base of the coil. This is known as a "condenser," and its action beautifully illustrates certain electrical phenomena, which we have not, so far, dealt with very fully. The condenser itself consists of sheets of tinfoil separated by plates of some good insulating material, such as mica or paraffined paper. These insulating plates are represented by thick lines in the figure. Alternate sheets of tinfoil are connected together, so that, when completed, the condenser electrically consists of two conductors of very large surface quite close together, separated from one another by a good insulating material, or *dielectric*. If, now, these two conductors are brought to different potentials, the dielectric between them will, as we have elsewhere explained,[1] become strained, and the production of this state of strain can only be brought about by the expenditure of energy. In the induction coil, the two conductors are respectively connected to the nut *h* and the spring *b*, both points on the primary circuit, but lying on either side of the break contacts at B.

Suppose, now, the current to be flowing in the coils P P, we know that a quantity of energy is stored as magnetic strain energy in the electro-magnet T T, and the surrounding medium. No energy is stored in the condenser, since its plates, C_1 and C_2, are practically at the same potential.

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[1] *See* page 396.

When, now, the battery circuit is broken at B, we have shown that the magnetic strain energy begins to return to the electric circuits, and so rapidly does the P.D. of the points on the two sides of the gap at B rise, that a brilliant disruptive spark would usually be produced there. But the plates C_1 and C_2 of the condenser are joined to the two sides of the gap, and as the P.D. rises some of the energy that would go to make the spark is, as it were, shunted to the condenser and stored as electrostatic strain energy in the dielectric. The P.D. across the gap, therefore, does not rise so high, and the spark, therefore, is much diminished, or "killed." This is one effect of using the condenser: the sparks at B are much less brilliant, and the platinum contacts are to some extent preserved.

But this is not the only effect. The stored energy of the electro-magnet being thus provided with another storehouse in the condenser, leaves the former much more quickly, or, in other words, the magnetic lines which represent the strain disappear much more rapidly than if the condenser were absent. Now, the inductive effect on the secondary circuit depends on the *rate of change* in the number of these lines passing through that circuit. This inductive effect is, therefore, very much increased by the presence of the condenser, and a much longer and more brilliant spark can be obtained between the knobs, *r r*.

There is also an effect when the primary circuit is re-made. We have just left the condenser with its plates at different potentials, or charges. But these plates, though there is a gap at B, are in conducting communication through the battery and the coil P P. Their potential-difference, therefore, cannot persist; they begin to discharge, and a current passes from C_1 through T_1 and the battery to T_2, and thence through the coil P P to C_2. This current, the rise and fall of which are retarded by the self-induction of the coil P P, it will be noticed, flows through P P in the opposite way to that in which the battery current would flow. If now the hammer H springs back and makes the contact at B before this discharge current has died away, the battery E.M.F. has first to neutralise the self-inductive E.M.F., tending to prolong this discharge current before it can set up its own current in the coil P P. Thus, the rise of the primary current is retarded, and the inductive effect of such rise is diminished. We therefore have a lop-sided effect between the knobs *r r*, the discharge at the break of the primary being brilliant, whilst that at make is either feeble or altogether absent.

This one-sidedness of the discharge from the secondary terminals of an induction, which has a condenser inserted in its primary current, must not be overlooked in discussing any results obtained. We regret very much that we have not space here to describe some of these very beautiful results with vacuum and radiant-matter tubes; we can only remark that experiments of this kind promise to reveal to us, perhaps in the near future, something more regarding the entity we call electricity.

As already remarked, the chief object of the various modifications of the induction coil just described was to increase the length and brilliancy of the spark obtained in the secondary circuit; in other words, to produce a current with an enormously greater voltage than the primary current. The fundamental law of transformation holds good, and this increase of pressure must be accompanied by a corresponding diminution in the current. In fact, under the most favourable circumstances, the best result we could get would be that the product of pressure and current *after* transformation should equal the corresponding product *before* transformation, or

$$\mathbf{A}' \times \mathbf{V}' = \mathbf{A} \times \mathbf{V}.$$

where **A** and **V** represent current and pressure in the primary.

But, turning from the highly specialised coil, the outcome of fifty years of modification and improvement, that is used with batteries as current generators for the particular purpose indicated, to the coils which satisfy the requirements of electric transmission by alternate currents, we find a great simplification. The latter coils, or "transformers," as they are now called, consist essentially of three parts—namely, two electric circuits, a primary and a secondary, and a magnetic circuit. The former consist, of course, of insulated copper coils, and the latter, in part at least, of well-laminated iron. Contact breakers, commutators, condensers, etc., are no longer a necessary part of the transformer, which is really one of the simplest pieces of electrical apparatus in practical use.

In most transformers one of the copper coils, or sets of copper coils, usually consists of many turns of fine wire, and the other of a few turns of comparatively thick wire. Since there is no contact breaker or subsidiary apparatus, either of these coils can be used as the primary to the other as secondary. If the thick wire coil be used as primary, as in the old induction coil, you obtain in the secondary a higher pressure but a less current. This is now called transforming "up." But if the fine wire coil be used as primary, the pressure in the secondary is lowered as compared with that in the primary, whilst the current is increased. The ratio of the effective pressures in the two coils is nearly that of the ratio of the number of turns on each, the coil with the greater number of turns having the greater pressure, and *vice versâ*.

Turning now to the magnetic circuit, it is usual to class modern alternate-current transformers according as this circuit is closed or open, that is, as to whether the magnetic lines run entirely through iron, except where they cross joints, or partly through iron and partly through air, or other non-magnetic materials. We shall describe one or two examples of each class.

Closed-Circuit Transformers.—In these the magnetic lines set up by the currents in the primary coil have provided for them a complete circuit of good magnetic material, and ample cross-section. A ring-shaped copper coil, entirely overwound with iron wire, or an iron ring, entirely overwound with the magnetising copper coils, may each be taken as representing a method of fulfilling the conditions.

Faraday's early transformer (Fig. 345) was, in fact, of the latter class, though, as the magnetising primary coil, A, did not cover the whole of the ring, there would be some leakage of magnetic lines through the air. It is now one of the objects of the design of this class of transformer to ensure that *all* the lines set up by the primary shall, if possible, pass through the secondary.

But though ring-shaped transformers are excellent from a theoretical point of view, they are not easily made on a large scale, and the effects can be obtained more readily in other ways. The essential details of a modern closed-circuit transformer will be understood by reference to Fig. 348, which shows the magnetic and electric circuits of the Lowrie-Hall transformer used by the House-to-House Electric Light Company of London. A number of soft iron plates, I I, of a convenient size, are built up into a bundle, with thin insulating paper between the successive plates, to stop the cross flow of eddy or Foucault currents. When the thickness required to carry the maximum number of magnetic lines has been obtained, two copper coils, which have been separately wound on formers, are slipped over the bundle. One of these coils, T, consists of many turns of fine wire, and the other, F, of fewer turns of thick wire, the ratio of the turns on the two coils being determined by the change of pressure the transformer is required to make. Two such bundles and coils are then placed side by side, and the ends of the plates bent over and interlaced, as shown in Fig. 348. The whole is fixed in a strong iron frame, and clamped tightly up; the corresponding coils on the two sides are connected in series, and the ends brought to terminals in a box at the side of the frame. This box also contains the fuses, which are placed on both circuits to protect them from a dangerous excess of current. These transformers are made of various sizes, capable of transforming from 1 to 40 horse-power, and of changing the pressure from 2,000 to 50 or 100 volts. Each horse-power transformed may be regarded as being able to light up 11 or 12 glow lamps of 16 candle-power each.

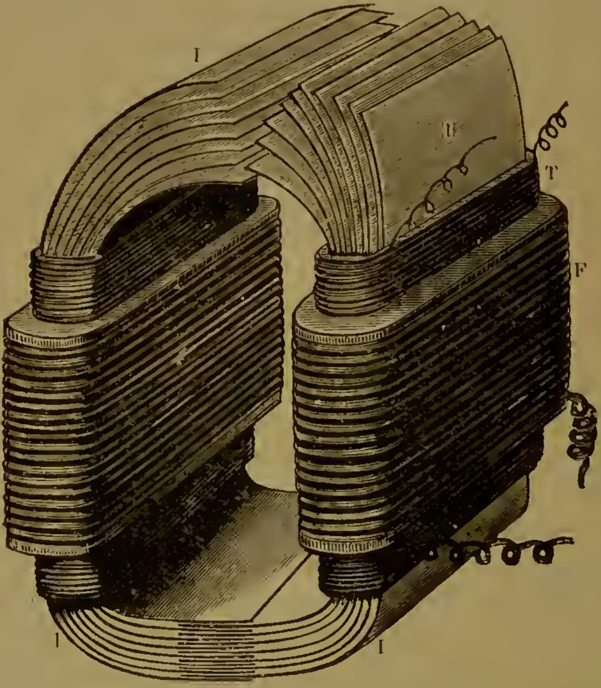

Fig. 348.—Method of Constructing the Lowrie-Hall Transformer.

In Fig. 349 is shown a much larger closed-circuit transformer, capable of dealing with 150 horse-power; it is of the pattern designed by Mr. Ferranti for use in the sub-

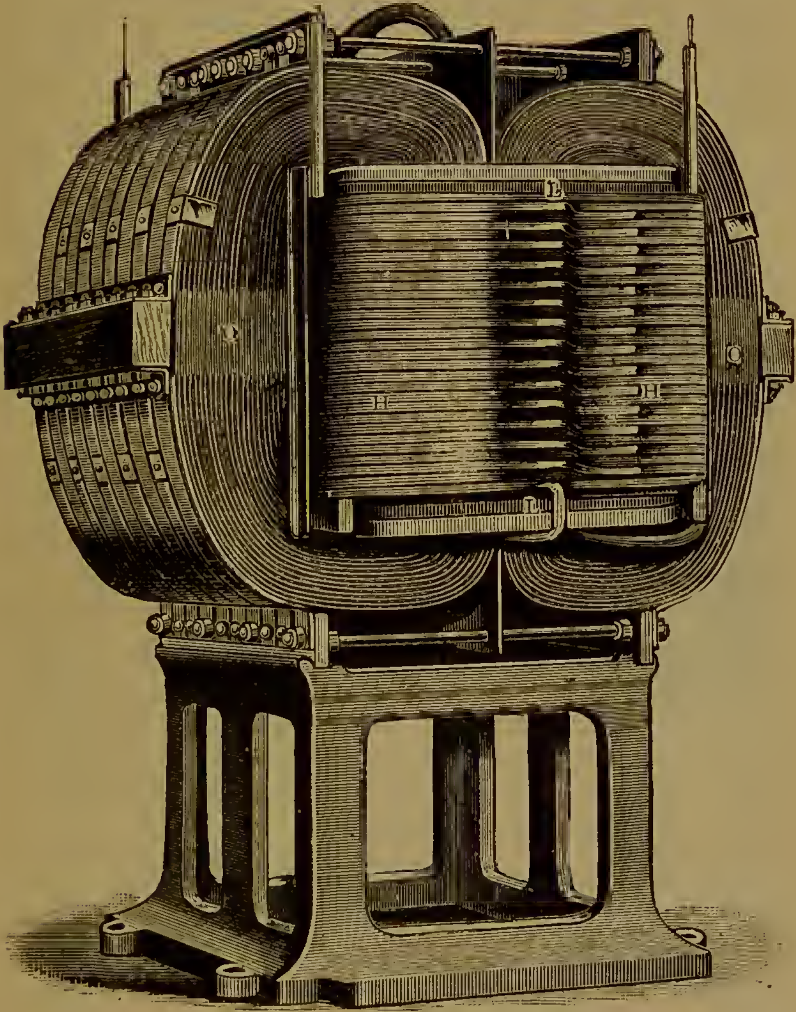

Fig. 349.—Ferranti 150 Horse-Power Transformer.

stations of the London Electric Supply Corporation, in the manner already described (page 668). The iron circuit is more laminated than that of the Lowrie-Hall transformer, bundles of hoop-iron laid side by side being used instead of iron plates. Each piece of hoop-iron forms a complete circuit for the magnetic lines of force, for its ends overlap and are clamped together tightly at O, where the only non-magnetic joint in the circuit occurs. The complete transformer has a double magnetic circuit, instead of a single one, as in the previous example.

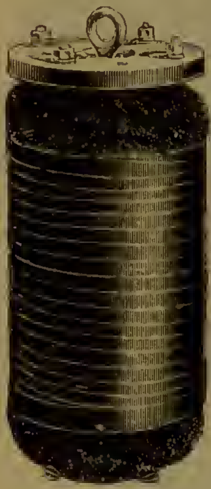

Fig. 350.—Swinburne's "Hedgehog" Transformer.

The high-pressure coils, H H, lie between two sets, L L, of low-pressure coils. Each set consists of flat sections built up of copper strips, carefully insulated with vulcanised fibre and shellac cloth; each section is separated from its neighbouring sections by layers of insulating material, and the various sections of each set are joined in series. The low-pressure coils are further insulated from the high-pressure coils by layers of ebonite and by air-spaces. When in use the whole transformer is immersed in an insulating oil; if, therefore, the insulation between the high- and low-pressure coils, or the high-pressure coils and the frame, should momentarily break down, this oil will flow back again and re-insulate the coils.

Open-Circuit Transformers.—The ordinary induction coil (Fig. 346), with its automatic break and condenser removed, may be taken as the type of an open-circuit transformer. The primary and secondary coils are wound round a simple straight iron core of iron wires, the magnetic lines from which have to complete their circuit through the surrounding non-magnetic materials.

A modern open-circuit transformer, built especially for power transmission, is shown in Fig. 350; it is the so-called "Hedgehog" transformer, designed by Mr. Swinburne. A gun-metal casting, with a cross-shaped section, passes down the centre, and is spread out at the bottom end to form the legs, and at the top to receive the board for the terminals. In the recesses of the cross four bundles of soft iron wire are laid, filling them up, and the projecting ends of the wires are spread out like the bristles of a brush, giving the transformer the prickly appearance at the ends from which its name is derived. The iron wires are taped over, and the thick wire coils wound on; over these are slipped two cylinders of ebonite, on which the fine wire coils are wound in two compartments, with an ebonite disc between them. The ends of both circuits are brought to terminals on the board at the top, and the whole is enclosed for protection in a stoneware jar, in which no eddy current can be set up, and which does not short-circuit the magnetic lines.

The relative advantages of closed- and open-circuit transformers have been the subject of much controversy, and a full discussion of them would lead us too far. We may, however, point out that the open-circuit transformers require more magnetising ampère-turns for the same magnetic flux; and since, in some systems, the practice is to have the primaries of all the transformers in a district permanently closed on the mains, large currents will be flowing even when the secondaries are open and no power is being taken from the transformers. On the other hand, it is asserted that the loss by "hysteresis"[1] is less in open- than in closed-circuit transformers, and also that, as there is more room, a greater cross-section can be used in the copper coils, and thus the losses due to the heating effect of the current be diminished.

We shall conclude this section with a description of the special transformer constructed by Mr. Tesla for his brilliant experiments on high-pressure and high-frequency alternate currents. In this transformer no iron is used, and the magnetic lines pass entirely through non-magnetic material. It is shown in section in Fig. 351. The low-pressure, or primary coils, P P, consist of well-insulated copper wire wound in two sections on the wooden

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[1] See page 156.

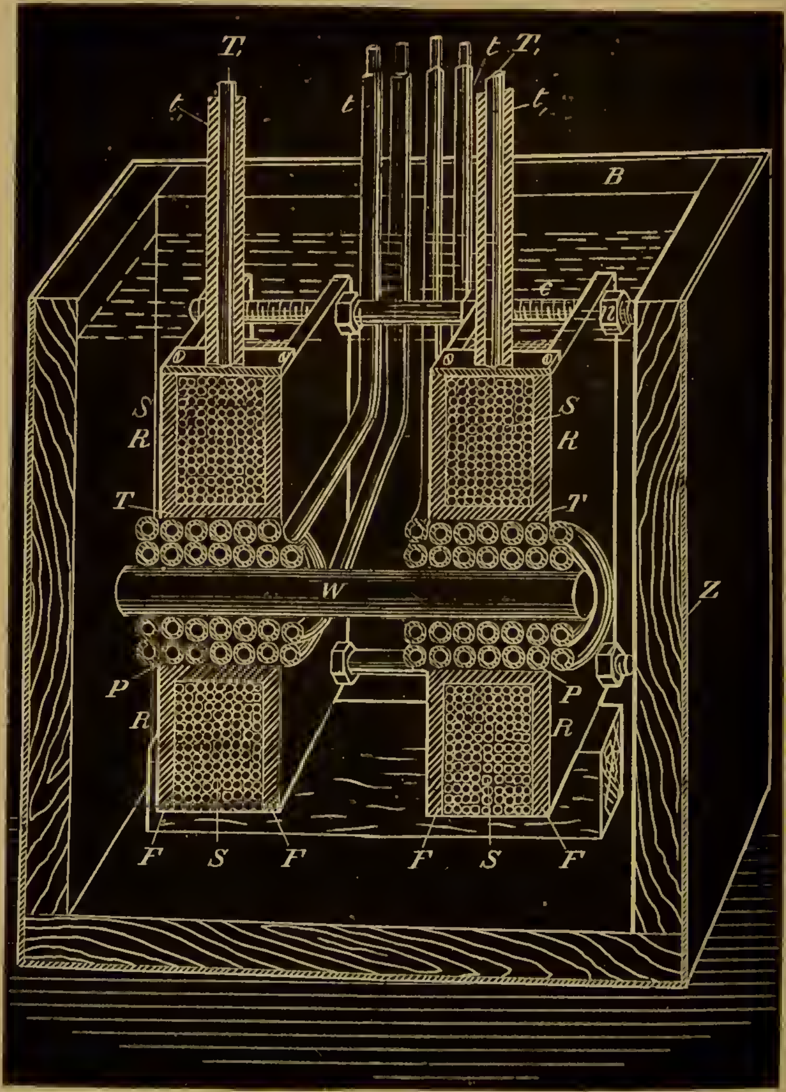

Fig. 351.—Tesla High-pressure Transformer.

mandril, W. There are four layers, each having twenty-four turns in each section, and the different layers are separated by cotton cloth. The ends of the sections are brought out through ebonite tubes, *t t*. The high-pressure, or secondary coils, S S, are wound upon ebonite bobbins, R R, which slip over the primary coils, P P. Each secondary coil consists of 260 turns of best gutta-percha-covered wire, and the two halves are wound oppositely, and connected in series. The ends, T T, are brought out through thick ebonite tubes, t_1 t_1. The bobbins are clamped firmly in their places, with wooden distance pieces between them, and the whole placed on wooden supports in a wooden box, B, surrounded by a shell, Z, of zinc, The box is filled with a good insulating oil, which, if a spark should pass, will close up again, and restore the insulation.

Electric Motors.

The problem of the Transmission and Distribution of Power by means of the electric current not only requires that the original energy, whatever it may be, should be economically converted into current energy, and also economically, by the use of transformers, or otherwise, conveyed to the points where it is required, but also that there should be at these points suitable apparatus for the conversion of the energy of the current into any other form of energy that may be required. Some forms of such apparatus we have already described when treating of arc and glow lamps, and also of electrolytic baths, but there yet remains for description that class of apparatus which is capable of converting the power of the current into the form in which it can be most widely applied, viz., ordinary mechanical power. The machines used for this purpose are called **Electric Motors**.

An Electric Motor may, therefore, be defined as *a machine for converting the energy of electric currents into mechanical* *energy by arranging for some current-carrying conductors to be free to move in a magnetic field.*[1] From this it is evident that an electric motor performs the converse operation to that accomplished by a dynamo. Not only is this the case, but it is extremely interesting to find that a good continuous-current dynamo can be used as an electric motor—in other words, that such a dynamo is a *reversible machine*. When used as a dynamo, and supplied with mechanical power from a steam engine or other prime mover, it transforms that power into electric-current power at a certain prearranged voltage. Conversely, if an electric current at a proper voltage be supplied to the machine from an external source, it will convert the power of that current into mechanical power available for driving machinery, or for any other purpose to which such power is generally applied.

The beginning of the history of electric motors dates back to a period anterior to Faraday's discovery of magneto-electric induction. Sturgeon, in 1823, described a piece o apparatus, consisting of a star wheel, by which mechanical rotation could be produced electrically. Also, since a current-carrying coil was known to be attracted by a magnet, motors were made in which such coils were pulled round by magnets. All these, however, were mere toys. The first motor which was constructed to do an appreciable amount of work was made by Jacobi, in 1838, for the purpose of propelling an electric boat on the Neva. This motor (Fig. 352) consisted of two sets of fixed horse-shoe electro-magnets, with their poles facing one another. Between these was placed a six-armed wheel, free to rotate on a horizontal axis, and carrying twelve straight electro-magnets, so spaced that, in certain positions of the wheel, their poles came opposite the poles of alternate pairs of the fixed magnets. On the axis of the wheel four split-tube commutators were so arranged that they changed the direction of the currents in the straight magnets when they came opposite the horse-shoe magnets, so that what was previously an attraction became a repulsion. In this way continuous rotation was produced, and using a large battery of 128 Grove's cells, Jacobi was able to drive his boat at a speed of 2·6 miles per hour. The experiments, however, cost the Emperor Nicholas about £2,400, and, therefore, did not seem to promise much practical usefulness for the new method of propulsion.

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[1] The reader should compare this definition with the definition of a dynamo given on page 186.

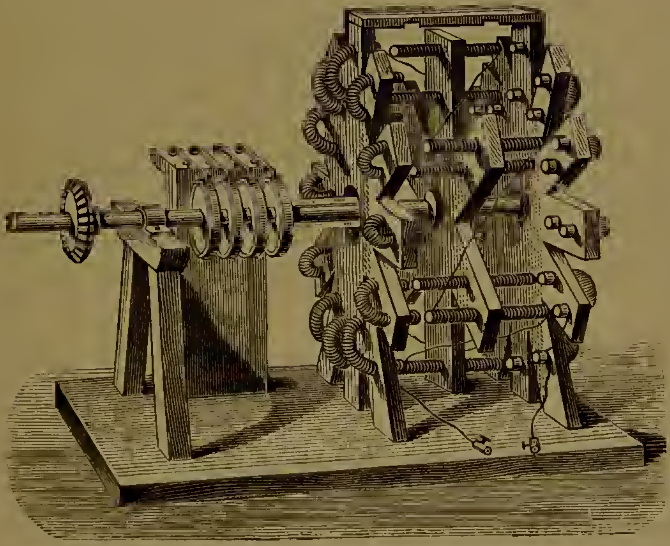

Fig. 352.—Jacobi's Electric Motor.

From time to time the subject of the construction of efficient electric motors attracted a good deal of attention, and numerous ingenious attempts were made by many inventors to solve the problem. One favourite device was to so arrange the machinery that by the attraction of soft iron cores into hollow solenoids a reciprocating motion was produced, like that of the piston of a steam engine. This reciprocating motion was then transmitted to the other parts of the machine in one of the usual ways.

Previous to the development of the dynamo machine, however, all these electric motors were severely handicapped in practical work by the high cost of producing the electric currents that were required to set them in motion. Primary batteries were the only sources available, and these, though very efficient, used far too expensive a fuel (zinc) to allow machines drawing energy from them to compete with steam engines. But when, by the improvement of the dynamo, electric currents drawing their energy from cheaper sources were made available, the aspect of the subject completely changed. In addition, the discovery that the dynamo was itself a reversible machine, and could be used as an electric motor, turned the attention of inventors in a new direction, which has been fruitful in producing the most important results.

It has already been pointed out that when the armature of an ordinary-series dynamo is rotated there is comparatively little resistance to the motion, as long as the electric circuit is not completed. But as soon as the outer circuit is closed a much greater effort is required to maintain the speed of rotation. In fact, it is from the work necessary to overcome this resistance to rotation that the energy of the currents is derived.

If, now, we reverse the experiment, and from some external source drive a current through the machine in the same direction as that which its own current would take in the above case; if, also, we hold the armature fast, so that it cannot move, then the same electro-magnetic and mechanical forces will be called into existence which resisted the rotation in the previous case. If, therefore, we release the armature and leave it free to rotate, it will move backwards and rotate in the opposite direction to that in which it was previously driven. Also, as the commutator, by continually changing the direction of the currents in the coils of the armature, maintains the effective relative positions of the field-magnets and armature currents unchanged, the rotation will be continuous. The rotating armature shaft can now be connected by belting or coupling to any machinery which it is required to set in motion, and, provided the resistance to rotation, so set up, be not greater than the tendency of the armature to rotate, the machinery will be set in motion and the required work will be done. In this way, from theoretical considerations alone, we can see that an ordinary-series dynamo may be used as an electric motor. With slight modifications the same reasoning, of course, applies to shunt- and compound-wound dynamos, but the case chosen is sufficient for our purpose. We shall now describe one or two modern forms of continuous-current electric motors, and afterwards return to some interesting elementary points in connection with the theory underlying their working.

Continuous-Current Motors.— As any good continuous-current dynamo is reversible, and can therefore be run as a motor, the difference in external appearance between motors and dynamos is not very marked, except in cases where the purpose for which the motors to be used has caused a departure from the ordinary dynamo types. For general purposes the actual differences are small, and are chiefly in internal details, such as more careful lamination of the iron to avoid eddy currents, and good mechanical devices for transmitting the drag on the current-carrying wires to the shaft.

A good example of a modern motor is shown in Fig. 353, which represents a motor manufactured by Messrs. Laurence, Scott and Co. It is of the double-magnetic-circuit type, similar to the dynamo described at page 235; in this case, however, cast-iron is used for the magnets, and the diminished permeability is counteracted by increased cross-section. Cast-iron is used so as to obtain greater ease and cheapness of construction. The iron core of the armature is slotted on the external periphery, and the wire is wound in these slots. In this way the magnetic pull on the wires when the machine is working is directly transmitted to the iron of the core and thence to the shaft, and also the iron projections prevent the wire being displaced laterally by the large forces called into play. The armature is drum-wound, and the conductors are brought to a 36-part commutator. Externally, the most marked difference is in the arrangement of the brushes, which are set vertically without any lead, and touching the commutator along the horizontal diameter. It will be seen that so set the armature can be run round either way without damaging the brushes; arrangements for so running are absolutely necessary in a

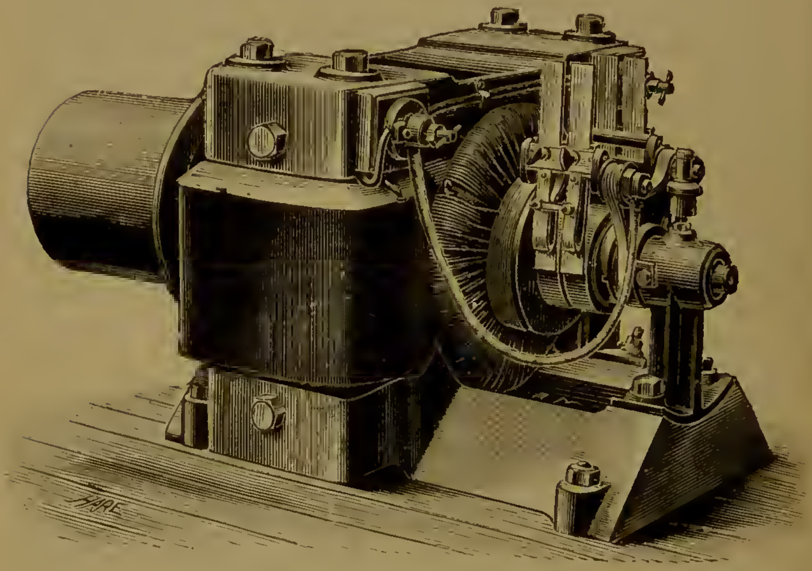

Fig. 353.—Laurence, Scott & Co.'s Motor.

motor which is to be used for general work, as the direction of motion may often have to be reversed.

As we have already very fully described the leading types of dynamos, we shall not further refer to the many excellent motors that so closely resemble them, but conclude with descriptions of two motors in which the ordinary dynamo form has been widely departed from. The exigencies of electric locomotion have led to the greatest modifications of this kind, and our examples both deal with motors designed for locomotive work.

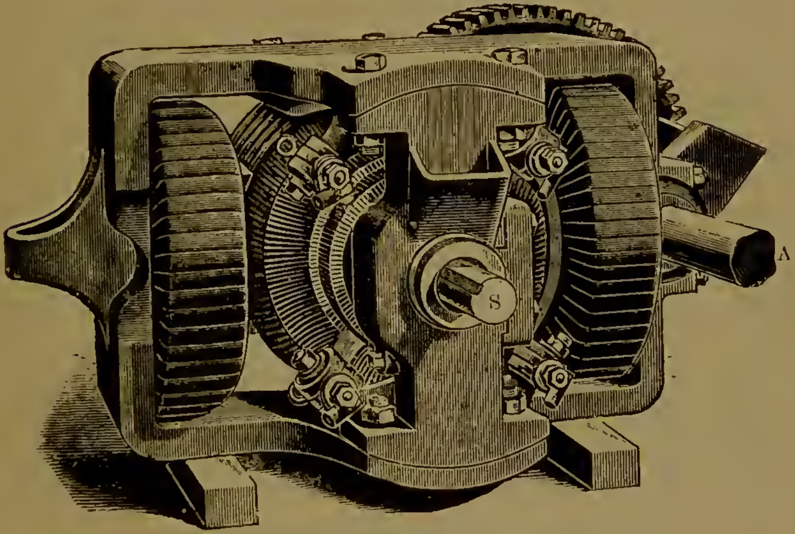

Fig. 354.—Edison Street-car Motor.

The first (Fig. 354) is a street-car motor, designed by Edison. For this kind of work the high speed of the armature, electrically necessary, is a disadvantage, and many attempts have been made to reduce the absolute speed of the armature, and also to simplify the gearing by which a still further reduced speed is transmitted to the axle of the car. In this case the motion of the armature spindle S is transmitted to the car axle A, by means of a single pinion and toothed wheel at each end of the spindle, one of these being partly shown at the back. The magnetic circuit has four poles, but only two exciting coils, which are wound upon the horizontal pole-pieces. The magnet frame is made in one piece of special soft cast-steel, a material which is at present on its trial for dynamo and motor magnets. To this frame the pole-pieces are bolted.

The number of revolutions per minute is reduced by making the armature of large diameter (18 inches), which increases the circumferential speed, and by passing four poles instead of two, an arrangement which causes each armature wire to cut through more fields in a single revolution. The armature is Gramme wound, and the commutator is very large, being 10 inches in diameter. The brushes are fixed to holders bolted to the four corners of the vertical pole-pieces. They are made of blocks of carbon pressed against the commutator by springs, and are so set that the armature can run either way without damaging them. The motor can develope 30 horse-power, and when running at 460 revolutions per minute, drives the car at a speed of 12 miles per hour. When in use the whole motor and transmitting gears are encased in a watertight cover.

Our next example (Fig. 355) has a still more curious magnetic circuit. The outer frame is in two parts, which, when the motor is in use, are bolted together, but in the figure one of them is shown raised to expose the interior. This frame forms the yoke of the magnetic circuit, the pole-pieces being placed one below and the other above the armature; the surface of the upper pole-piece can be seen inside the casing. It is round this upper pole-piece that the single exciting coil employed is wound, the pole-piece projecting far enough inwards from the frame to make room for it. The frame when closed so completely covers both field-magnet and armature coils that water can be poured over the motor with impunity, or it may be run through water up to the lower side of the bearings.

The armature is 20 inches in diameter, and is ring-wound, the wires lying in 64 grooves in the iron core, each groove taking 14 windings; these grooves can be distinctly seen in the figure. The commutator is substantial, and the carbon brushes are fixed in stationary brush-holders clamped to the frame on each side of the bearing. The driving pinion is on the left-hand end of the armature axle, and drives a large toothed wheel on the car axle, by which the motor is supported. Both pinion and wheel are enclosed in a water- and dust-proof cover, which is partly filled with heavy lubricating oil in which the gearing works noiselessly.

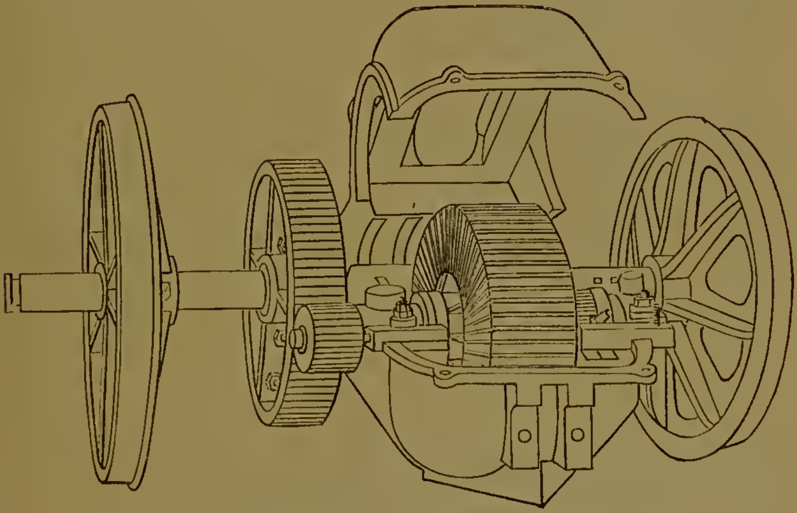

Fig. 355.—Fifty Horse-power Waterproof Tram-car Motor.

This motor is capable of developing 50 horse-power. It is made by the General Electric Company of New York, and in October, 1892, was in use on about 150 tram-lines throughout the United States.

It is unnecessary to further multiply examples of actual motors, and we shall now conclude this section with a few remarks on some interesting points in the theory underlying their working.

Elementary Theory of Electric Motors.—We have shown (page 698) that if a current from an external source be driven through a series dynamo in the *same* direction as that in which its own current would flow, the armature, if free, will rotate backwards. If allowed to rotate, however, new electrical conditions are brought into existence. The following experiment is both instructive and interesting. Suppose the source of current used to be a secondary battery of constant E.M.F. Connect the battery to the dynamo and place an ammeter in the circuit. First hold the armature fast, so that it cannot rotate, and read the current indicated by the ammeter; let this be, say, 20[1] ampères. Now let the armature rotate slowly, and it will be noticed that the current at once becomes *less.* Record the speed and the current, the former being, say, 50 revolutions per minute, and the latter 16·2 ampères. Let the armature rotate faster and faster, and take simultaneous readings of speed and current for different speeds. It will be found that as the speed increases the current diminishes, and *vice versâ,* until at a high speed, say 195 revolutions per minute, the current sinks to 5·1 ampères, a fraction only of its value when the armature was kept motionless.

The cause of this diminution of current is not far to seek; on it, in fact, depends the capability of the electric motor to absorb the energy of the electric current and convert it into mechanical energy. Consider the condition of affairs when the armature is allowed to spin. You have then conductors moving in a powerful magnetic field. Under these circumstances, E.M.F.'s must be (*see* page 178) set up in these conductors. Moreover, since the armature is rotating *backwards*, these E.M.F.'s must be such as would tend to generate a current in the opposite direction to that usually given by the machine—that is, they tend to generate a current in the opposite direction to the current actually flowing through the machine; in other words, with respect to the actual flow of current, they are *back E.M.F.'s*. That this must be their direction is also apparent from *Lenz's law* (page 174), and from considerations of the conservation of energy, from which it is clear that where there is no store of energy the effect cannot assist the cause, but must act against it.

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[1] The figures given are taken from an actual experiment.

The fundamental fact, then, is, that when an electric motor is working in any circuit it sets up a back E.M.F. in that circuit, which tends to cut down the current. Let $\mathbf{E}$ represent the E.M.F. of our battery in the above case, and $\mathbf{R}$ the resistance of the circuit. Then, when the armature is held at rest, we have by Ohm's law that the current ($\mathbf{C}_o$) in the circuit is given by the equation—

$$\mathbf{C}_o = \frac{\mathbf{E}}{\mathbf{R}}.$$

But when the armature is allowed to rotate, a *back* E.M.F. (e) is set up in the circuit, which diminishes the effective E.M.F. available, and alters the current, which is now given by the equation—

$$\mathbf{C} = \frac{\mathbf{E} - \mathrm{e}}{\mathbf{R}},$$

which shows that $\mathbf{C}$ is necessarily less than $\mathbf{C}_o$.

This last equation may be re-written in either of the forms—

$$\mathbf{C}\,\mathbf{R} = \mathbf{E} - \mathrm{e},$$
$$\text{or } \mathbf{E} = \mathbf{C}\,\mathbf{R} + \mathrm{e}.$$

These are *pressure* equations, and the last expresses the physical fact that the volts ($\mathbf{E}$) generated by the battery are partly employed in driving the current, **C**, through the dead resistance, **R**, of the circuit, and are partly balanced by the back volts, **e**, set up in the armature of the motor.

The last equation becomes still more suggestive, from the physical standpoint, if we multiply each term by the current, **C**, and the time, **t**, when it takes the form—

$$\mathbf{E\,C\,t = C^2\,R\,t + e\,C\,t.}$$

This equation is now an energy equation each term, when ordinary units are used representing so many joules[1]. The term on the left-hand side gives the total electrical energy in joules thrown into the circuit by the battery during the time **t**. The first term on the right represents, as we have seen (page 653), the number of joules that are wasted in heating the conductors carrying the current **C**. What, then, does the last term represent? It is obviously in amount equal to the difference between the total energy given to the circuit and the energy wasted in heating the conductors. But mechanical energy is being produced by the motor, and the law of the *conservation of energy* asserts that energy cannot be created. The maximum amount of this mechanical energy must, therefore, be sought for in the missing energy represented by the last term of the above equation. This term, in fact, represents the amount of energy (diminished in the actual case by some unavoidable losses due to mechanical and magnetic friction) transformed into mechanical energy.

It is interesting to consider the various factors of the term, **e C t**, which represents the transformed energy. One of these is **e**, the back E.M.F. of the motor, and when **e** is zero the term itself becomes zero; that is, when the armature is held fast, no electric energy is transformed into mechanical energy, which is otherwise obvious. In other

[1] *See* page 673.

words, in the case considered, as long as there is no back E.M.F., and consequent diminution of the current, there is no transformation of energy, there is no electric motor action. But it is still more important to observe that the amount of energy transformed, *cœteris paribus*, is directly proportional to the back E.M.F., and, therefore, if we have some means of keeping up the magnitude of the current (for instance, suppose it generated by a constant-current dynamo), the quicker we allow our armature to rotate, the more mechanical energy can we draw from it in a given time.

Without troubling our readers with the more complicated equations in connection with shunt- and compound-wound motors, we may remark that the corresponding "transformation" term, as it may be called, has the same form as that given above, the only difference in the meaning of the symbols being that **C**, the current, instead of being the whole current supplied to the motor, is that part of it which passes through the armature.

Reactions in the Armature.—In the chapter on dynamo machines we briefly referred (page 220) to certain reactions in the armatures of continuous-current dynamos, the chief effect of which was to make it necessary to move the brushes forward, so as to avoid destructive sparking on the commutator. In an electric motor the same kind of reactions occur, but they have an opposite effect on the position of the brushes. That this must be so is evident when we consider that for the same relative positions of the magnetic fields due to the armature and the field-magnets, the armature *runs round in the opposite direction.* Since the position of the brushes for no sparking depends only on the two magnetic fields, it will still be the same as before, but as regards the *direction of rotation* will be reversed. In other words, the *forward lead* in a dynamo becomes a *backward lead* in a motor. In connection with this it will be interesting to compare Fig. 356, which represents the effective field of a motor, with Fig. 120, representing the effective field of a dynamo. In both cases the direction of rotation is supposed to be clockwise, instead of being reversed in the first case, as we have been considering. The similarity of rotation is brought about by reversing the armature current in Fig. 356, as compared with Fig. 120, and obviously the effect of such reversal will be to rake the resultant field in the opposite direction, as depicted in the figure.

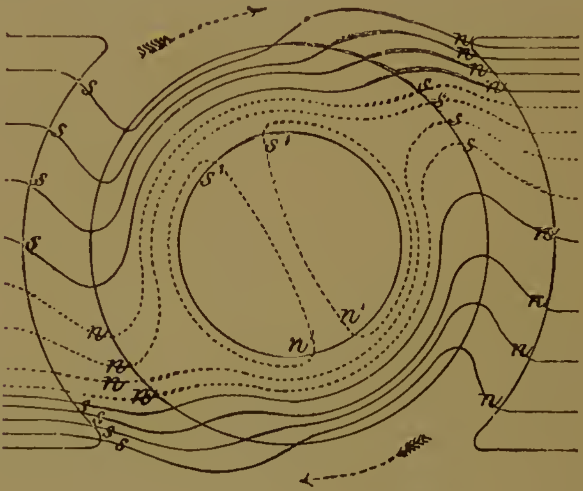

Fig. 356.—Twisted Field due to Armature Reaction in a Motor.

There are many other interesting points in connection with the theory of continuous-current motors. The investigation, either theoretical or experimental, of the conditions affecting the relations between the electric current and pressure supplied, on the one hand, and the speed, turning moment and efficiency, on the other, lead sometimes to curious results. For such investigations we must, however, refer the student to special treatises, as they are beyond the scope of this book.

Alternate-Current Motors.—Consider the case of an alternate-current dynamo such as we depicted in Fig. 124, with permanent steel magnets for its field-magnets. If the armature be supplied with a suitable alternate current, and be once got into rotation at the proper speed, the machine will act as a motor with somewhat peculiar properties. One remarkable property will be that whatever the load,[1] within a certain maximum limit, the speed will be absolutely constant, and will depend only on the number of alternations per minute of the current supplied. For it is obvious that to set up a back E.M.F. of a frequency equal to that of the E.M.F. of the generator, there must be a definite number of reversals per minute of induced E.M.F. in the armature coils, and these can only take place at one definite speed. If an attempt be made to exceed the above maximum load, the machine, instead of simply slowing down, will stop dead, and will not again start of itself, although the load be reduced below the maximum. To start such a machine, the armature must first be spun at nearly the proper speed, when it will begin to absorb power from the supply current, to the requirements of which it will quickly adjust its speed.

It is obvious that such a motor, which cannot start itself, is of little practical use; though the fact that its speed is constant when once it is started, is in its favour. The same difficulty is met with when it is attempted to use a modern alternator with separately excited field-magnets; and the availability of such a machine for motor purposes is further diminished by the necessity for having a separate continuous current to excite its field-magnets.

We may, therefore, conclude that, although under certain conditions the ordinary alternate-current dynamo can be used as a motor, it is not generally available for motor purposes, and more especially is useless where the only source of electric energy obtainable is from an alternate-current system on public supply mains.

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[1] By the *load* is meant the amount of mechanical power which the motor is called upon to give out at the time under consideration.

There is one direction in which a solution appears possible. The armature of an ordinary continuous-current *series*-wound motor will rotate in the same direction whichever way a continuous current be sent through it. This is due to the fact that when you reverse the current you reverse both the magnetic field due to the armature and also that due to the field-magnets. Since *both* are reversed, the mutual action between them is in the same direction as before, and therefore the armature still rotates the same way round. Now, if the direction of rotation be the same for both positive and negative currents, the machine should work with an alternate current, which is simply made up of such positive and negative currents. Unfortunately, in practice, serious difficulties present themselves, due to the secondary reactions that become prominent whenever the current is reversed. The iron of the field-magnets does not reverse its magnetism quickly enough in large machines, however carefully it be laminated. The solution has, therefore, only been successful with small motors.

Other attempts have been made to solve the problem of producing a satisfactory self-contained electric motor to be actuated by ordinary alternate currents, but hitherto without sufficient success to warrant us devoting space to the consideration of them. This want of a satisfactory motor is a disadvantage in alternate-current systems of public supply.

Polyphase Alternate-Current Motors.—By far the most successful alternate-current motors are those which use polyphase currents, the particular kind of currents hitherto employed being three-phased. The chief drawback to the use of such motors in the electric transmission of power is that three-line wires are required instead of two.

In our description of the Shallenberger meter, at page 454, we have already minutely explained how a rotating magnetic field can cause a disc of iron placed in it to revolve. The action is due to the fact that such a disc consists of a number of closed electric circuits, in which currents are induced which react on the rotating field, causing the disc to revolve. The same principle is used in polyphase motors, but the revolving disc, instead of being a solid block, consists of a number of carefully wound electric circuits, each closed on itself, and so placed that the induced currents are confined to circuits in which they shall give the maximum turning effort. Were a solid block of copper used, the induced currents would wander about in all directions, and much power would be wasted by them in heating the copper. The power so wasted in the Shallenberger meter is insignificant, because the whole amount of power transformed is very small.

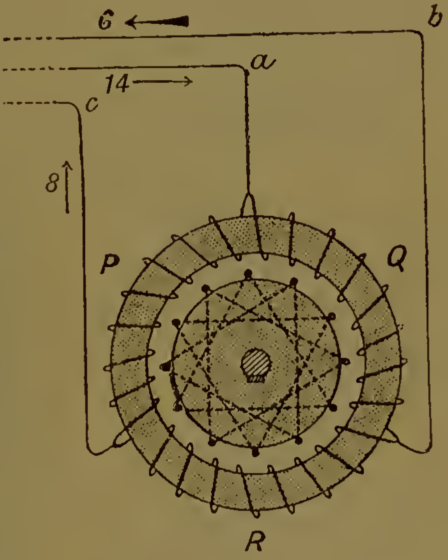

Fig. 357.—Diagram of Polyphase Motor.

A "polyphase motor," then, consists of an arrangement for producing a rotating magnetic field, in which are placed closed electric circuits, free to rotate on an axis. The arrangement is diagrammatically depicted in Fig. 357, which is due to Dr. S. P. Thompson. The three phase currents are brought to the magnetising coils by the line-wires, *a*, *b*, and *c*. It will be remembered that the peculiarity (*see* page

460) of these currents is that they reach their positive (or negative) maxima at successive instants, following one another at intervals equal to one-third of the period of a complete alternation. Thus, the maximum positive current in *b* occurs one-third of a period after the similar current in *a*. The poles produced in the iron ring within the coils P, Q, and R will obviously follow the fluctuations of the magnetising currents in the coils, and as the maxima of the currents follow one another round and round, so will the magnetic field in the enclosed space rotate.

This enclosed space is nearly filled with a cylinder of laminated iron, on the circumference of which a series of closed electric circuits are wound. Each circuit consists of three conductors, or sets of conductors, 120° apart on the circumference, and the currents induced in these circuits by the rotating field cause the iron cylinder to rotate, because of the reactions already explained.

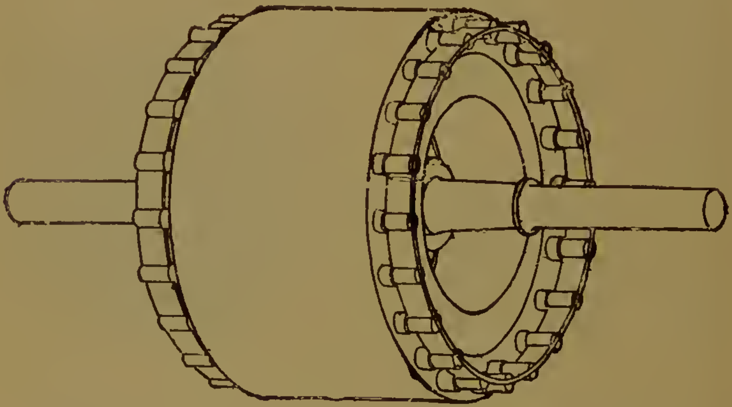

Fig. 358.—Rotating Part of Polyphase Motor.

Large motors of this kind have been built by Mr. C. E. L. Brown, of Oerlikon. Fig. 358 represents the rotating part of a motor which developes 20 horse-power at a speed of 1,200 revolutions. The core discs are pierced with longitudinal holes near the circumference, and the copper conductors are round bars threaded into these holes. It is therefore impossible to displace them by the mechanical forces set up. The ends of the copper bars are simply connected by circular strips of copper; there are no sliding or other contacts, since no external currents have to be introduced, the whole of the working currents being induced currents set up by the rotating field produced by the external part of the motor, which is not shown.

Applications of Power Electrically Transmitted.

There have now been described, in perhaps sufficient detail, the various systems and apparatus that are employed for economically transmitting to a distance large amounts of power by electrical means. Also the various interesting laws governing the action of the electric motors which receive this power and re-convert it into mechanical forms have been referred to, and some of the motors themselves described. There still remains the question of the application of this power as received from the electric motors. At first sight the considerations involved would seem to be purely mechanical, and therefore such as need not be dealt with in a book on the Electric Current. But the mechanical conditions react upon the electrical problem, and cause modifications in the solution, which in themselves are interesting both from an electrical and a general point of view. The remainder of this chapter will therefore be devoted to the description of a few of these applications.

ELECTRIC LOCOMOTION.

One of the most interesting applications of the mechanical power supplied by means of the electric motors just described is that which utilises it for purposes of locomotion, whether in the form of electric railways, tram-cars, launches, or any other of the numerous methods by which passengers are conveyed from place to place.

For many reasons the supply of the necessary power for these purposes in the form of an electric current has several obvious advantages over the use of other kinds of power. In the case of railways, some of the nuisances attendant on the use of steam have been met, or rather minimised, by confining the locomotives to specially-constructed roads from which ordinary vehicular and pedestrian traffic is rigidly excluded. But notwithstanding this partial seclusion of the furnace and its attendant smoke, the steam locomotive is at the best a tolerated nuisance in towns and thickly-populated districts, whilst all of us would enjoy our railway travelling better if the air of the numerous tunnels in certain parts of the country were not fouled by the furnace smoke.

The attempts to make use of steam on ordinary roads have not been particularly successful. Steam tramways have been universally condemned as unmitigated nuisances by the residents along the line of route, and in many cases have had to cease running as such; whilst the steam traction engine has only found very limited applications, and these chiefly in country places.

But when we turn to the use of electrical power, all the social conditions are changed as if by magic. The smoke and foul air disappear, and instead of the ponderous locomotive we have, at the worst, a special motor car attached to the train or tram-car. In many cases, moreover, the motors are attached to the axles of the vehicles themselves, so that no separate engine or its equivalent is required, but the electrically propelled vehicle moves along in silent obedience to this most wonderful of the servants that man has yet subdued to minister to his own wants.

In dealing with the applications of electric motors to purposes of locomotion, we cannot simply confine ourselves to describing how the power is transmitted from the motor shaft to the wheels of the vehicle, but must consider the whole system used, and more especially how the current is supplied to the motors. Thus in the case of launches, dog-carts, tricycles, and so forth, which do not run upon a specially laid down and restricted track, the source of the current must obviously be carried by the conveyance itself. With tram cars, whose course is restricted to the rails laid down for them, the current generators may either be carried on the car, or the current may be supplied from a central station by means of an insulated conductor which follows the course of the track. Passing on to railways, we find that to attain ordinary speeds the electric power required cannot at present be economically obtained through the medium of any current generators carried on the train, and that this power must therefore be transmitted to the moving train through a suitable conducting circuit.

Owing to a variety of causes electric traction has, during the last few years, made much more rapid progress in the United States than it has in the United Kingdom or in Europe. Nevertheless, a fair amount of solid though quiet work has been done on this side of the Atlantic, and such installations as have been carried out are distinguished by their soundness and thoroughness. In selecting examples from the great quantity of material available, we must follow the same course as we did when describing modern dynamos, that is, to take such as seem most suitable for our general plan, but we must not be supposed thereby to condemn systems or installations which are left unnoticed. Up to the present, electric tram-cars, or street railways as they are called in the United States, have perhaps attracted most attention, and shall therefore be dealt with first.

Electric Tram-cars.—As just pointed out, the electrically driven tram-car can either carry its current generators with it, or, since it follows a definite and prescribed route from which it cannot deviate, the necessary current may be brought to it by means of conductors which follow the line of route from end to end.

In the first of these cases, that in which the car carries its own store of energy, it is quite obvious that the current must be generated by chemical methods, and that dynamos are out of the question. For the latter would require to drive them some source of mechanical power such as a steam, gas, or oil engine. Now a little consideration will show that, if such a prime mover be used, it will be far more economical to apply the mechanical power generated directly to the object in view—that is the propulsion of the car—rather than face the inevitable losses of the double conversion, first of mechanical into electrical, and secondly of electrical back again into mechanical power. Moreover, such a combination would have all the disadvantages of the steam locomotive, with a few others incidental to itself.

The only method, then, practically available in a self-driven electric tram-car is that the current should be generated chemically, that is, that either primary or secondary batteries should be carried on the car itself. In a previous part of the book (page 64) it has been shown that although the generation of the electric current by primary batteries is highly efficient when regarded as a mere transformation of energy from one form to another, yet practically the cost of the materials at present available is absolutely prohibitive for industrial purposes. This consideration limits the choice still further, so that, in actual practice, secondary batteries are the only current generators that at all satisfy the working conditions at the present time.

It may be pointed out here, before proceeding to the consideration of details, that the chief reason why cars driven by secondary batteries can enter into competition with cars driven by other methods, is that the secondary batteries derive their store of energy from the energy of burning fuel as supplied through the medium of the boiler, steam engine, and dynamos used to charge them. Also that when the energy stored in the batteries has been practically used up, that is, when the batteries are discharged, they can obtain another supply of energy from the same commercially economical source.

Secondary Battery Cars.—The batteries, which have been described at page 85, are placed underneath the seats, where they can be quickly changed from the outside. The cells are made of special shape to fit the recess they have to occupy, and the plates and acid are contained in lead-lined boxes instead of glass ones, which would be liable to be broken. They are joined together in sections which fit into separate compartments. At the sides of the latter are solid copper contacts, so placed that, when the cells are slid into position, corresponding contacts on each section make firm connection with the car contacts, thereby joining up the cells to the circuits, which are under the control of the driver.

The replacement of the discharged cells by freshly-charged ones can be effected in a time not greater than that required to change horses in a horse-car. The car is run between two empty shelves placed at the right height, and doors at its sides opened exposing the batteries, which are quickly slid on to the shelves. The freshly charged cells standing on other shelves are then either raised or lowered hydraulically to the proper level and slid into their places, automatically making the necessary contacts as just described. In some cases other methods are used, in which the car, after the removal of the discharged cells, has to be hauled to another position to receive the charged ones.

The next step, in logical sequence, would be to describe the electrical and mechanical details of the transmission of the current from the battery to the motors, and the arrangement of the latter on the car. These details, however, are much the same in principle, whether the current is generated on the car or brought to it by external conductors, and will be more conveniently dealt with after the description of the various methods of using external conductors for the supply of the electric energy.

But before leaving the question of secondary batteries on tram-cars, a word or two may be said about their advantages and disadvantages as compared with the rival systems. Of course the one great advantage is the abolition of the external conductors with their heavy first cost and all the complications attendant upon their use and maintenance. There is also the saving of the energy lost by the heating of these long conductors with the heavy currents that have to be transmitted when large numbers of cars are to be driven. But against this saving there has to be set the usually greater loss of energy, consequent upon the double transformation, that has to be faced in the charge and subsequent discharge of the secondary batteries. The greatest drawback, however, to the more general use of secondary batteries for tram-car propulsion is their great weight in comparison with the energy which they store, or perhaps, to speak more accurately, in comparison with the electric power which they can steadily generate, or which they may be called upon to supply in frequent emergencies. This heavy dead-weight adds considerably to the total weight of a car, even when filled with passengers, and thus increases the power which has to be spent in moving the car. Could the weight of the batteries be safely reduced to a fraction, say even one-fourth or one-third, of that found necessary with the cells as at present made, there would doubtless be a wide extension of the use of secondary batteries in this direction.

Transmitted Power Tram-cars.—The second method of supplying the necessary electric power to the motors on the tram-car is to generate the electric current by means of stationary engines and dynamos at some convenient point on or near the line of route, and to convey it to the moving cars by fixed conductors running parallel to the rails. With regard to the generation of the electric current by means of stationary engines and dynamos, sufficient has been already said in the previous sections of the book to give the reader a fair knowledge of the principles involved and of the most important details. The outstanding differences between a central station for the supply exclusively of electric power, and one for the supply of electric light, are entirely of technical interest. Perhaps the one point that may be mentioned is that, according to present practice, the pressure at which the current is delivered to the mains for traction work is usually from 400 to 500 volts.

Turning now to the mains or conductors themselves, the general method employed is to carry the current to the motors on the cars by a single insulated conductor or system of conductors, and usually, but not always, to employ the rails on which the cars run for the return conductors to complete the circuit. As these rails, being uninsulated, are in conducting communication with the earth, part of the current will return through the earth. In fact, the rails and the earth are conductors in parallel circuit (*see* page 288) with one another, and the current to be transmitted will be divided between them according to the usual rule, that is, inversely as their respective resistances. Some of the consequences of this division of the return current will be referred to later on.

The methods of running the insulated conductor may be divided into two chief and, from a constructive standpoint, essentially different classes. This conductor may either be overhead, running alongside or over the middle of the track, or it may be a conductor on or in the ground, but of course well insulated, between the rails. The first method is usually referred to as the "trolley" system, since a little overhead trolley has to be dragged along the wire by the car so as to pick up the current from the wire by means of a sliding or rolling contact. On lines where the traffic is heavy it is not possible to make the overhead wire of sufficient cross-section to carry the whole current required by all the cars that are out at once, since the weight of copper to be supported would be too great. When this is the case, armoured cables, or other kinds of buried conductors, are laid alongside the track and connected to the overhead "trolley" wire at suitable "feeding" points, as they are called.

The second method above referred to may also be subdivided into two classes. In one which is most generally used for ordinary tram lines, the insulated conductor is laid in a conduit between the rails. The upper cover of this conduit, which is flush with the street pavement, is slotted so that a trailer from the car above can pass down and make some kind of sliding connection with the insulated conductor within. Another method is to have the insulated conductor in the form of a third rail between the other two; but, for obvious reasons, this cannot be used in the crowded streets of a town. Its use is, therefore, confined to unfrequented country roads, to piers, &c., and to enclosed railways.

Trolley Lines.—As already explained, the distinguishing feature of the trolley system, and, it may also be remarked, the one which is always most obtrusively prominent to the passers-by in the streets through which the lines run, is the stout overhead copper wire, or rod, slung from pole to pole along the line of route. The cars are worked electrically in parallel[1] with one another, so that the current at the generating end of the line at any instant is the *sum* of the currents which each car in motion is taking at that moment. Owing to the heavy currents which are required by each motor, the conducting wire cannot be of the slender dimensions of an ordinary telegraph or telephone overhead wire ; for, though such a wire were to carry the necessary current without fusing, or even getting red-hot, the fall of pressure along the line due to the combined effects of its high resistance and the large current would be so great as to make the whole system uneconomical and unworkable.

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[1] *See* page 288 for an explanation of this term.

As already pointed out, the use of buried feeders tends, where the traffic is heavy, to diminish the size of the overhead conductor. But, however freely feeders may be used, the trolley wire itself is bound to be of an unsightly size, and hence has raised up a host of opponents amongst those whose æsthetic tastes lead them to conserve the amenity of their cities or towns, at the cost of diminishing the facilities for cheap and rapid intra-urban transit. That their objections are not altogether fanciful will be admitted by anyone who has had an opportunity of seeing the state of the main streets in many large towns in the United States.

The appearance of a tram-car on a line where a trolley wire is used is shown in Fig. 359, in which it will be noticed that the wire, and the mast on the top of the car by which the current is conducted from the wire to the car, are somewhat prominent objects. The particular car illustrated is one used on the South Staffordshire system, which was erected by the Electric Construction Corporation some two or three years since. The line for the greater part of its length runs along country roads, so that some of the objections to the use of a trolley wire in towns do not hold. In this case the wire is a rod of solid copper 0·34 inch in diameter. Feeders are freely used in the shape of heavily armoured cables, buried at the side of the track and connected to the trolley wire through suitable fuses at half-mile intervals.

The supporting posts are steel columns, with neat projecting arms fixed at a height of about 21 feet above the roadway.

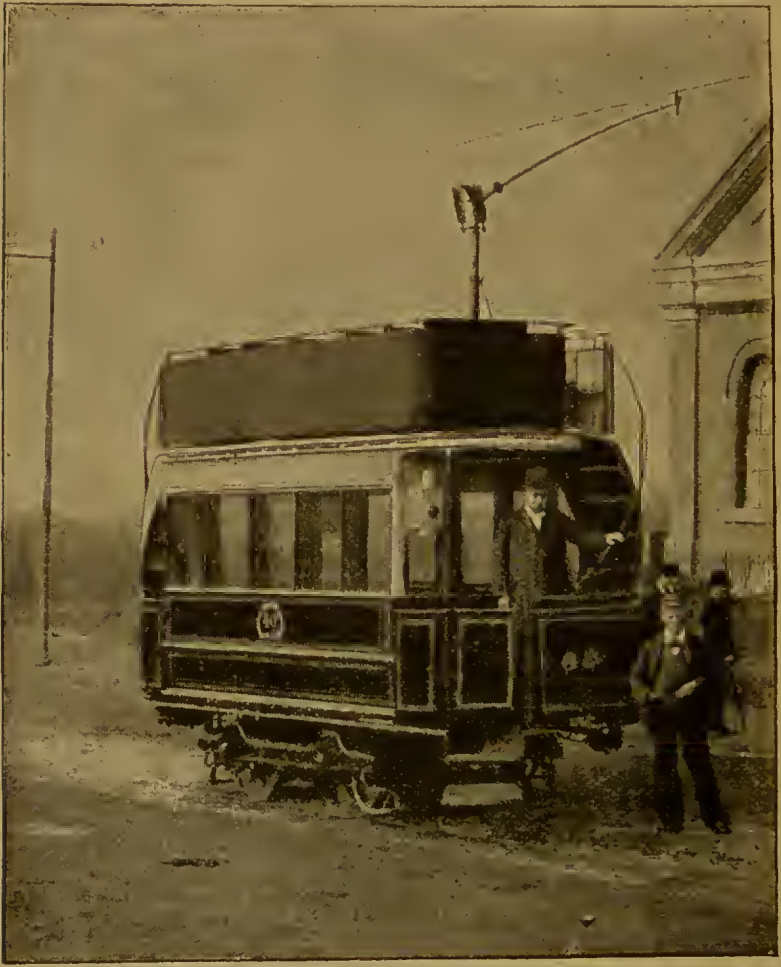

Fig. 359.—Tram-car with Overhead Trolley Wire.

The non-engineering mind is sometimes puzzled in trying to make out how the trolley can pass the arms which support the conducting wire. The mystery is at once solved when it is explained that the wire is suspended *under* the cross-arm, and does not pass over it as in the case of the familiar telegraph wire. Moreover, the trolley consists of a little gun-metal wheel, which is pressed by strong springs firmly against the *lower* surface of the wire, and which therefore runs freely under the cross-arm.

To make this explanation quite clear to our readers we give in Figs. 360 to 362 details of the principal parts. Fig. 360 is a side view, parallel to the wire *a a* of the insulator, as it hangs down from the supporting arm, whilst Fig. 361 is a cross-section at right angles to the wire of the same insulator. It will be noticed that the wire *a a* is supported by a kind of stirrup attached to the bolt B. This bolt is embedded firmly in the insulating material I, which fills the inside of the inverted bronze cup C, and this cup in its turn is firmly clamped to the projecting cross-arm.

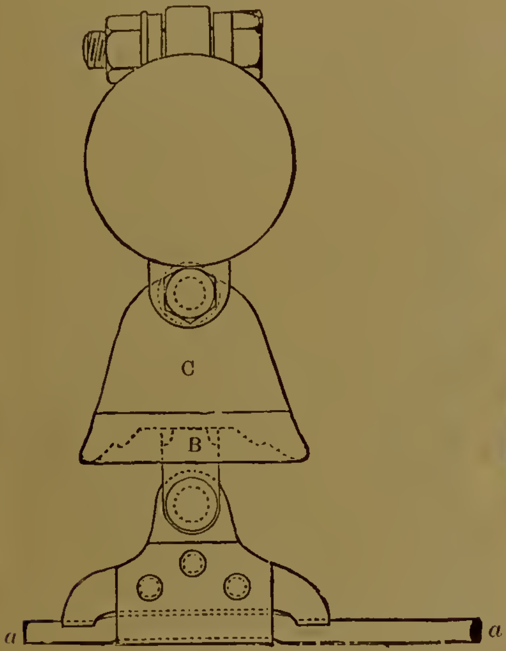

Fig. 360.—Insulator with Trolley Wire.

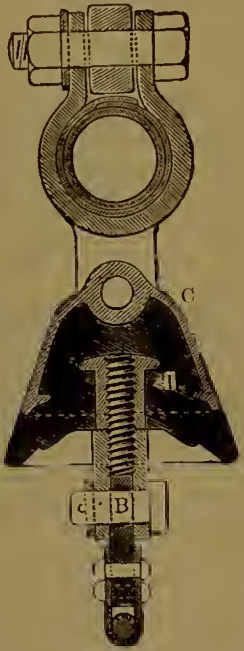

Fig. 361.—Section of Insulator

Figs. 362 and 363 show the details of the top and bottom of the flexible mast which is attached to the car. In Fig. 362 the letters C and *a* refer to the same parts of the insulator and wire as in Fig. 360. The trolley wheel W, made of gun-metal, and $2\frac{1}{4}$ inches in diameter, is fixed in a block B, which carries a pin *p*, turning freely in a support, as shown, on the top of the mast M. The lower end of this mast (Fig. 363) is jointed at J to an upright rod R, which drops into a hollow post fixed to the roof of the car. An arm A projecting from this rod carries one end of the strong spiral springs S, the other ends of which are attached to the

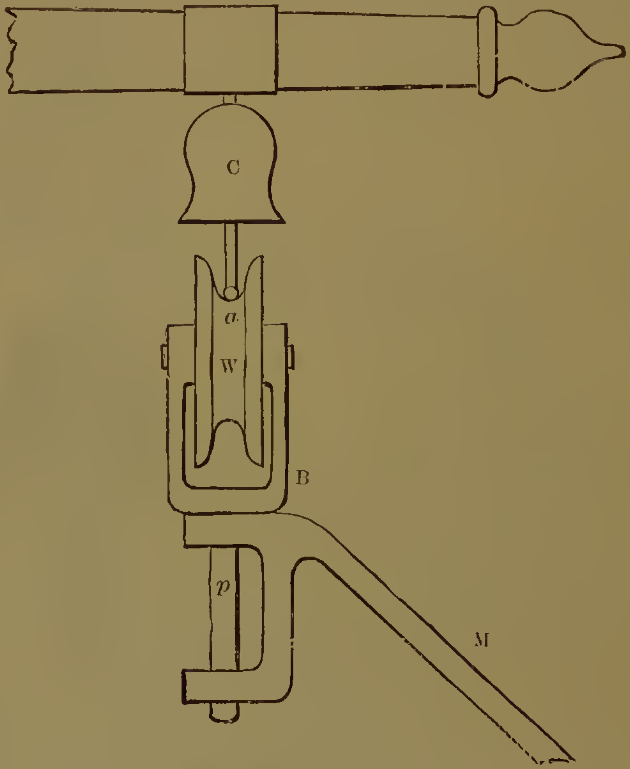

Fig. 362.—Trolley Wheel in Contact with Conductor.

mast M at some little distance from the joint J. The mast is, therefore, a long lever with very unequal arms, the fulcrum being at J, and the pull of the springs being brought on at only a little distance from J. From the freedom with which both the mast and the trolley wheel are mounted, they can easily follow the overhead wire in its varying positions relatively to the top of the car. The mast is also flexible, and therefore springs upward where the trolley wire is a little farther away than the average, being pressed back again where the wire once more approaches.

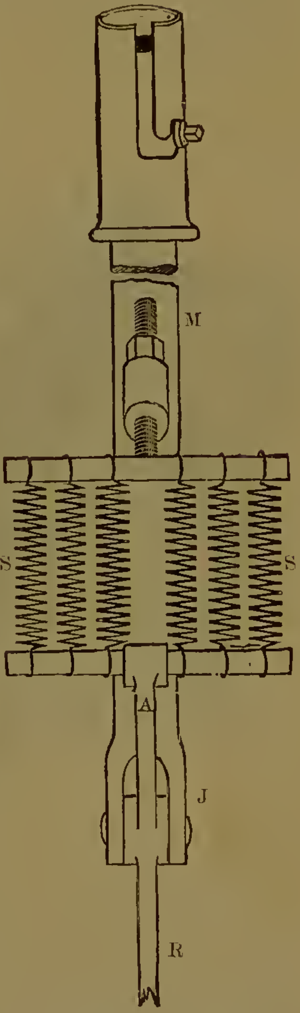

Fig. 363.—Lower End of Flexible Mast.

There are other ways of designing the trolley wheels and the flexible mast and their connections, but the general principles involved are much the same, and the above example will perhaps be sufficient to illustrate them.

Conduit Lines.—That the unsightly trolley wire is not an absolute necessity is shown in Fig. 364, which illustrates some of the details of a system designed by Mr. Love, and first used on the North Chicago Street Tramways at the end of 1891. In systems of this type some kind of covered conduit or trough, in which the insulated conductor or conductors are placed, is laid between the rails throughout the whole length of the track. The upper cover of the conduit is flush with the street, but is slotted parallel to the rails, so that some kind of trailing arm, projecting from underneath the car as it passes along, slides in the slot and makes connection with the conductors within.

In Fig. 364 the conduit consists of a long cast-iron

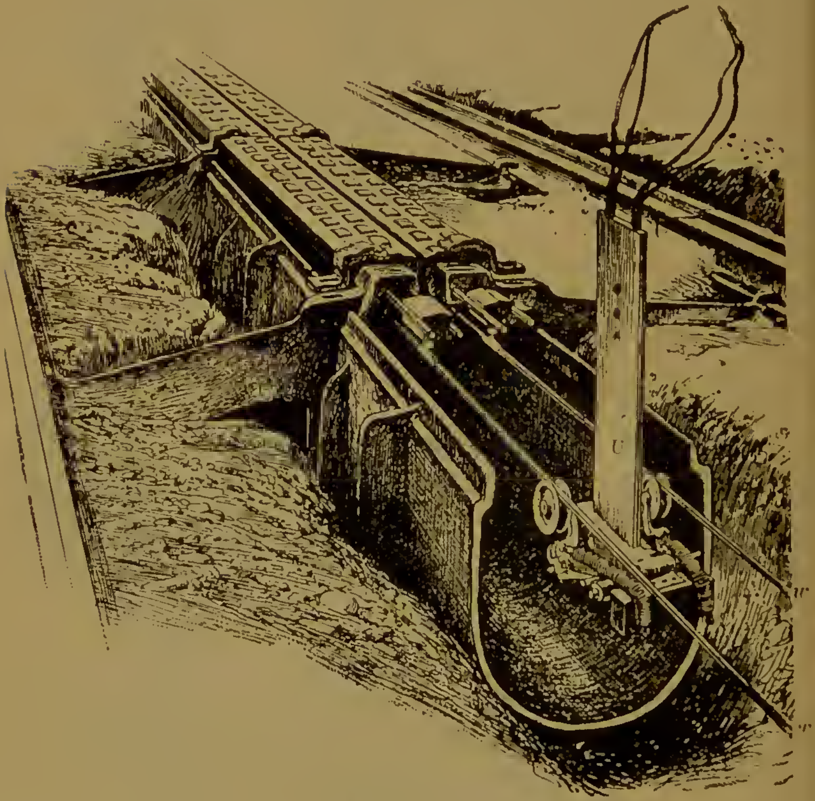

Fig. 364.—Love's Electric Conduit for Tram-lines.

trough held in place by stays projecting from the rails on either side. The top of the trough is covered with lengths of rolled steel; so designed that they can be quickly removed and replaced whenever it is found necessary to open up the conduit for any purpose. The conducting wires *w w* are supported inside the trough by insulators at short intervals, attached to brackets which project from either side just underneath the steel covers. These steel covers have deep flanges on the edges next to the slot for the purpose of preventing mischievous persons from tampering with the wires, which are, of course, bare, by poking sticks, &c., through the slot.

The sliding connector by which the current is taken to and from the car is shown in the figure detached from the car so that the details may be more clearly seen. The upright part U consists of two sheets of metal, insulated from one another, and respectively in conducting communication at their lower ends with the two wheels which roll underneath the conductors. The current passing from the wire to one of these wheels travels up the plate on that side, passes through the motor on the car, and returns to the other wire by the plate and wheel on the other side.

In the system just described *both* conductors are insulated, but in many conduit systems the conduit encloses only one insulated conductor, the rails and earth being used to complete the circuit as in the trolley systems. The use of only one insulated wire simplifies the details of the system, and cheapens the cost of construction, but electrically it is much less perfect than the use of two wires, and moreover an uninsulated return path may cause disturbances on neighbouring telegraph and telephone circuits.

As compared with trolley lines, the conduit lines are obviously more costly to lay down in the first instance, and also to maintain in proper working order. For the conduits are liable to become choked up with dirt and dust from the road, as well as to be filled with rain-water. They must, therefore, be continually under careful supervision, and be cleansed at frequent intervals. To diminish the cost of maintenance to some extent, conduits have been devised with a flexible cover fitting over the slot; this cover is lifted by the car and relaid again as it passes. In any case, however, the cost of keeping the conduit in order must be a serious item.

The other method of laying the conductor underneath the car instead of carrying it overhead is partly illustrated in Fig. 365, which shows one of the Electric Tram-cars on the pier at Southend. In this method, as already explained, a third conducting rail properly insulated is laid between the two running rails at very nearly the same level. A contact brush attached to an arm projecting from the car rubs on the top of this rail and carries the current to the motor, whence it returns to the generating station by the ordinary rails and earth. Anyone, therefore, touching the insulated rail is liable to receive an electric shock; but the newspaper accounts of any occurrences of this kind have usually been very highly coloured. Still, the inconvenience is sufficient to restrict the use of the method to cases where the line

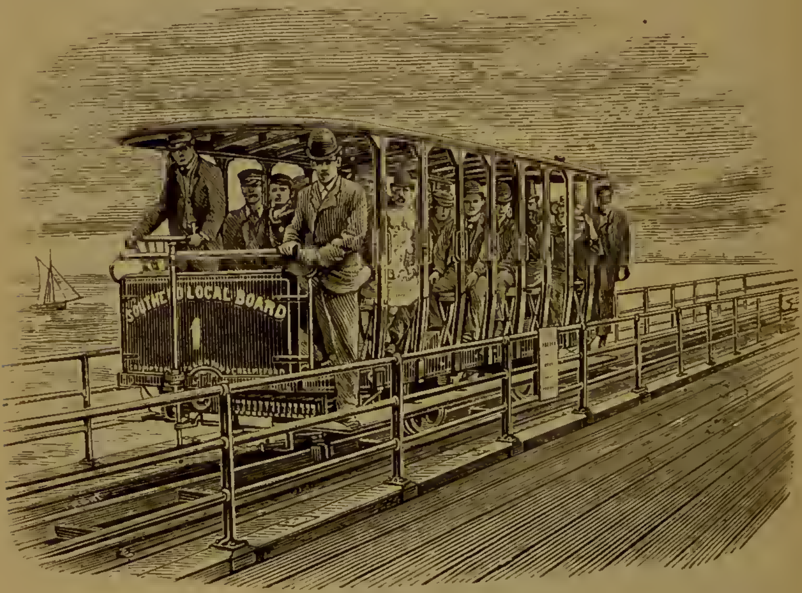

Fig. 365.—A Mid-Rail Tram-car.

can be completely enclosed, such as that shown in the figure, or more especially to railways, in connection with which more details will be given.

We cannot, however, leave this part of the subject without referring more fully to the use of the running rails and the earth for the completion of the return circuit. Such use must give rise to large currents in the earth; the paths of these currents cannot be restricted, but may spread out to a considerable distance from the line. The currents may, therefore, find their way into neighbouring circuits, especially if the latter are also using earth returns. Where these circuits are already carrying heavy currents no serious disturbance need be apprehended. But where the currents used are small, and the instruments in circuit are delicate ones, serious consequences may ensue. Thus telephone circuits may be rendered completely useless, because the effects depended upon are produced, as we have seen, by minute variations of the currents employed, and these variations will be completely masked by even a small fraction of the tram-line current passing along the wires. One obvious remedy is for the telephone people not to use an earth return, which, though cheap, is objectionable (see page 640) from other points of view. But naturally, as is the case in many English towns, a telephone company which has already established a complete system, working fairly satisfactorily with some hundreds of circuits, does not like to have all its circuits rendered inoperative by the appearance of a later comer in the form of a tramway company. The question of "Cheap Traction *versus* Defective Telephone Systems" is therefore already a burning one, and is likely to become more so in the immediate future. Another objection to the use of an earth return for heavy currents is that gas and water pipes into which the current finds its way may, and do, become corroded, especially at the joints where electrolytic action is set up.

Motor Trucks and Cars.—Having shown how the current may be brought to the car, the next point is to make clear how it is used thereon. The primary object of the electrical arrangements is to pass the current through the motors which are placed underneath the floor of the car, and geared in some way to the axle of the running wheels. The space available for the motors is very limited, and therefore, although any good continuous current dynamo will run as a motor, specially designed motors are required to satisfy the peculiar conditions. Two types of these have already been described (pages 701 to 703 in the section devoted to motors), and an examination of Figs. 354 and 355 will give the reader a general idea of how the motor is placed beneath the car. In each figure part of the running axle is shown, and it will be noticed that the axle carries part of the weight of the motor; the remainder of the weight is taken up by an attachment either to the floor of the car above, or to a bogie frame in which the whole of the running machinery is fixed.

One arrangement of the motors underneath and hanging from the floor of the car is shown in Fig. 366, which represents in side elevation and plan the position of the motors as designed by Mr. Holroyd Smith for the Bradford electric tram-cars. In this case the shaft of the motor carries a worm wheel, as shown at W, which gears directly into a toothed wheel fixed on the running axle. The lines $a\ a$ $a_2\ a_2$ of the armature axles therefore run fore and aft as regards the car, instead of transversely, as in the motors previously described. Of these armatures there are four, but there are only two sets of field-magnets, M and M_2, with pole-pieces at either end, between which the armatures revolve. The arrangement shows how adaptable the principles we have discussed are to the special exigencies which may arise in their applications. It may be interesting to note that with a brake-test the motors and gearing had a combined efficiency of 65 per cent., which is an extremely satisfactory result.

Another method of attaching the motors to a separate frame on which the car is built is shown in Fig. 367, which represents a " Motor Truck " very widely used in the United States. The arrangement of the motors can be clearly seen, as well as the toothed gearing by which the motion of the armature is transmitted to the running axles.

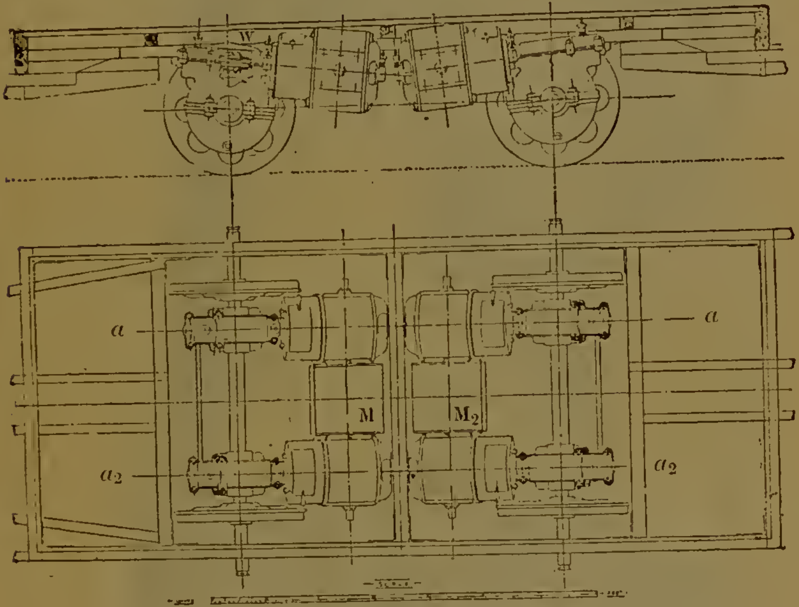

Fig. 366.—Under-frame of the Bradford Tram-cars, showing Motors, Side Elevation, and Plan.

The reduction of speed is made in two steps. Referring to the right-hand motor, it will be noticed that the front end of the armature axle carries a pinion which gears into a large toothed wheel. The axle of this wheel passes between the field-magnet limbs, and in its turn carries a pinion on the other side, which directly engages another large toothed wheel fixed on the running axle. In this way the high speed of the armature is reduced at the running axle to the ordinary speed of rotation required for tram-car work.

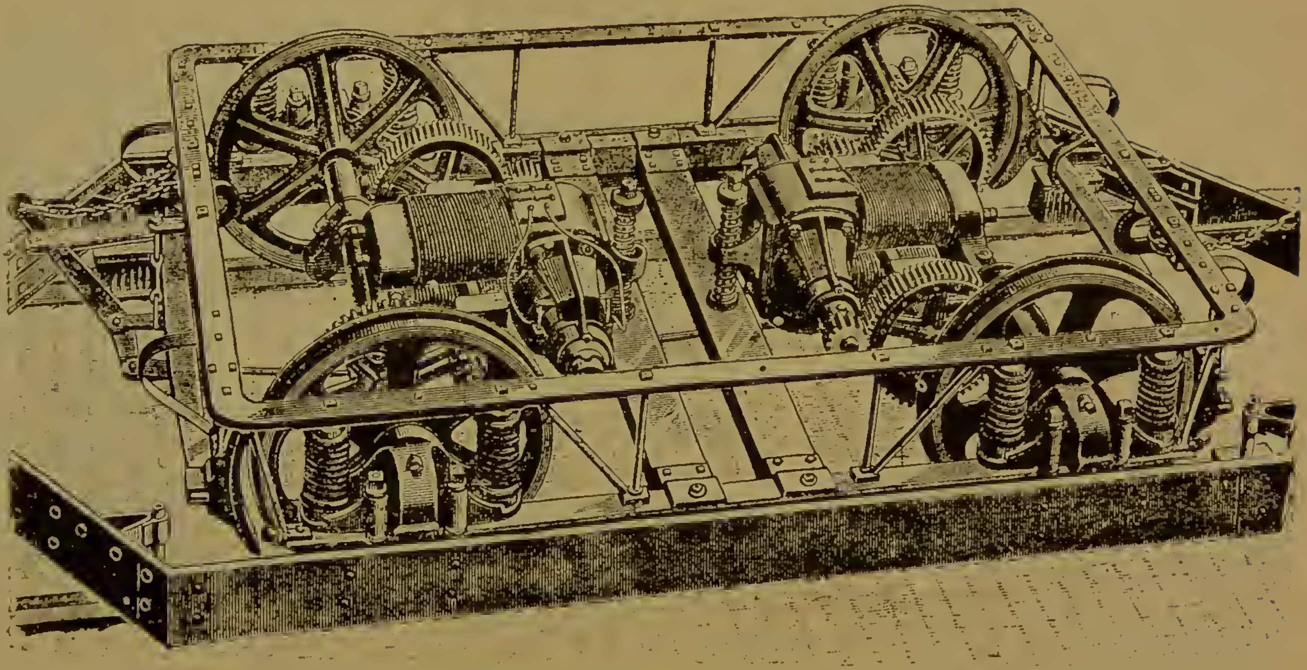

FIG. 367.—SPRAGUE MOTOR TRUCK, AS USED IN AMERICA.

There are many other ways in which the problem has been successfully solved, but the above two examples will give the reader a good idea of the general trend of the solutions.

The motors and their commutators, &c., must in all cases be so protected that mud or dirt cannot get to the running parts, and enclosed so that when necessary a hose can be brought to play upon them without danger of weakening the electrical insulation of the various circuits.

Switching Arrangements.—Perhaps the most interesting details in connection with tram-car work are the arrangements for switching the current on and off the motors. Certain well-defined and interesting electrical principles, not well understood by the ordinary public, have to be kept clearly in view. Of these, the chief is the fact that when a motor armature is standing still it is merely a dead resistance of copper wire, and moreover an extremely low resistance. Consequently if full pressure be put directly on to this resistance there will be an enormous flow of current, since the mains will be very nearly short-circuited. There is one advantage in this heavy current, in that it gives a maximum torque or turning effort, which is exactly what is required at the moment. But as the armature begins to turn, and, almost proportionally to the speed at any time, a back E.M.F. or pressure is introduced into the circuit which will cut down the current and eventually at full speed bring it to its proper value. But what is to be done during the interval whilst the speed is below the maximum? Obviously the large current above referred to cannot be allowed to flow, for serious consequences would certainly follow.

The difficulty is partially met by using series-wound motors (*see* page 216), that is, motors in which the field-magnet circuits are in series with the armature. In this way the armature can never be placed as a single resistance across the mains. But this of itself is not sufficient. The further arrangements depend upon the way in which the electric power is supplied.

In accumulator-cars the initial pressure can be reduced, and at the same time a larger current safely supplied by splitting up the battery into sections, and joining these sections in parallel instead of in series (*see* pages 664 to 666). Accordingly the starting switch is so arranged, that when the car is standing or running slowly, the sections are more or less in parallel. As the speed, and therefore the back-pressure of the motors increase, the switch is moved over, putting the sections more in series until finally at full speed all the sections are in series.

In trolley and conduit lines the full pressure is always on the mains, so that other methods must be adopted of reducing the pressure at the armature terminals at low speeds. By far the most convenient is to use a dead wire resistance, the whole of which is thrown in at the moment of starting, and which is taken out of circuit in sections, by moving the switch as the speed increases. The method is very wasteful, as the dead resistance absorbs the electric energy by turning it into heat which cannot be utilised, though proposals have been made to heat the car with it in winter.

Where there is more than one motor, an additional regulation for varying speeds can be obtained by placing the motors in series or parallel. The maximum turning effort is required when the car is being started up a steep gradient, and from this to running freely down the same gradient all possible variations in the amount of power demanded may be experienced. The arrangements possible with the motors shown on Fig. 366 are diagrammatically represented in Fig. 368. The first, in which all the armatures are "in series," is for ordinary running. The "intermediate" connections are for heavy running or easy starting, whilst the armatures are put "all in parallel" for the heaviest work. In this way the total turning effort put orth can be varied through wide limits. In each case it should be noticed that a resistance is placed in series with the armatures. A further regulation is possible by having the field-magnets wound in sections, and coupling these up in various ways.

But there is the interesting question of "reversing." A little consideration of the electro-magnetic phenomena upon which the action of the motor depends, will show that a reversal of all the currents will not reverse the direction of rotation of the armature, since it will leave the interaction of the magnetic fields due to the currents in the armature and field-magnets the same as before. The *reversing switch* has therefore to be arranged so that it reverses the current either in the armature or in the field-magnets, but not in both.

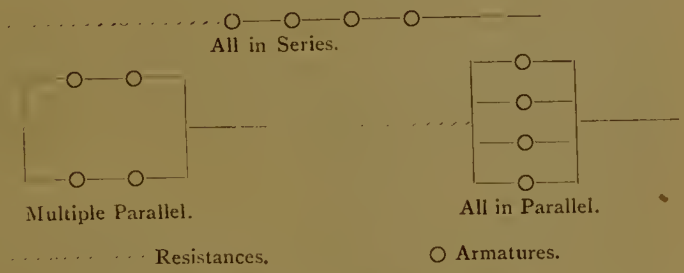

Fig. 368.—Diagrammatic Arrangement of Motor.

Lastly, there is the possibility of using the motors as a brake to bring the car quickly to rest. To do this when the car is running at full speed, all that is necessary is to first switch off the driving current and then either short-circuit the armature, which may be dangerous because of its low resistance, or close the circuit through a suitable resistance. In either case the armature will at once act as a dynamo armature, absorbing mechanical energy and converting it into electric energy. As the mechanical energy used is taken from the energy of the moving car, the latter is quickly brought to rest. Of course, in making these changes, the field-magnets should be kept energised; and therefore, as series-wound motors are at present almost universally employed for traction work, this brake action of the armature is not easily utilised.

Electric Railways.—Under this heading it is intended to refer to schemes which more nearly approximate in their importance, and the character of and method of working the traffic, to the functions of a steam railway rather than to the more lowly tramway. In the United States the term is applied to the meanest tram-line, provided only it be worked electrically. These glorified tram-lines are exceedingly numerous in the States, but of true electric *railways*, in the sense in which the term is employed in England, there are comparatively few. The two classes, however, merge into one another, and it must be admitted that it is impossible to draw a hard-and-fast line.

The first electrically-worked line in these islands at all approximating to a "railway" was the Portrush and Bushmills line in the north of Ireland. This line, at first six miles long, was constructed in 1882 under the direction of Dr. Siemens and Mr. Traill. The source of power is a waterfall on the river Bush, which is used to set in motion turbines which drive the generating dynamo. The current is taken to a raised insulated rail of T-iron placed between the running rails, from which it is picked up by travelling steel brushes and passed on to the motors, whence it returns by the uninsulated running rails.

The above line is, at the best, but a "light" railway. The work of heavy electric railway engineering in the United Kingdom was really inaugurated by the opening of the City and South London Railway in November, 1890. Although this line is only $3\frac{1}{4}$ miles long, it is a true railway in the English sense of the word. The stopping-places are stations with proper platforms, and exits and entrances, and the rails and tracks are similar to those used on ordinary railways.

Not only does the opening of the City and South London line mark the starting-point of electric railways with us, but its construction marks a new epoch in urban railway engineering. The lines are laid in two iron tubes driven through the ground at a depth of 60 to 70 feet below the surface, and therefore low enough to avoid all sewers, gas and water pipes, subways, &c. They follow the direction of the main thoroughfares above, but were constructed without disturbing the surface except at the points where the stations were to be placed. The difficulty of efficient ventilation at such a depth has been ingeniously overcome by making the trains nearly fill the cross-section of the tube or tunnel, so that as they pass through they drive out the air before them through the shaft of the station in front, drawing in a fresh supply by suction from the station just passed. Since there are two tubes, one for the "up" and the other for the "down" line, the dangers of collision are minimised.

In the generating station, which is at one end of the line, there are three large dynamos, each capable of developing 300 electrical horse-power, at a pressure of 500 volts. Two of these are sufficient for ordinary requirements, the third being held in reserve. They are driven by suitable and separate steam engines.

From the dynamos the current is taken by massive lead-sheathed cables to distributing boards in the signal-boxes, whence it is led by lighter conductors to the feeding-points on the insulated working conductor. The latter consists of a specially rolled steel rail which is carried on glass insulators between and about one inch below the level of the running rails. Each length is electrically joined to the succeeding length by copper strips, thus ensuring good electrical continuity. The current for each locomotive is picked up from this insulated rail by three cast-iron shoes which slide along it; after passing through the regulating resistances and motors it returns by the ordinary running rails to the dynamo house.

Each train is drawn by a separate locomotive as in ordinary railway working. One of these, as constructed by Messrs. Mather and Platt from the designs of Dr. Hopkinson, is shown in Fig. 369. The general arrangement differs from that which has been described for tram-car work in that the motor armatures are built upon the axles of the running wheels, thus avoiding all gearing, with its complications and loss of power. The field-magnets are very massive, and are placed in an inclined position as shown, being supported partly by the frame of the locomotive and partly by the wheel axle. The motors are series-wound, as is usual in electric traction work, and reversal of the motion is effected by means of a special switch which reverses the current in the armature, leaving that in the field-magnets unchanged.

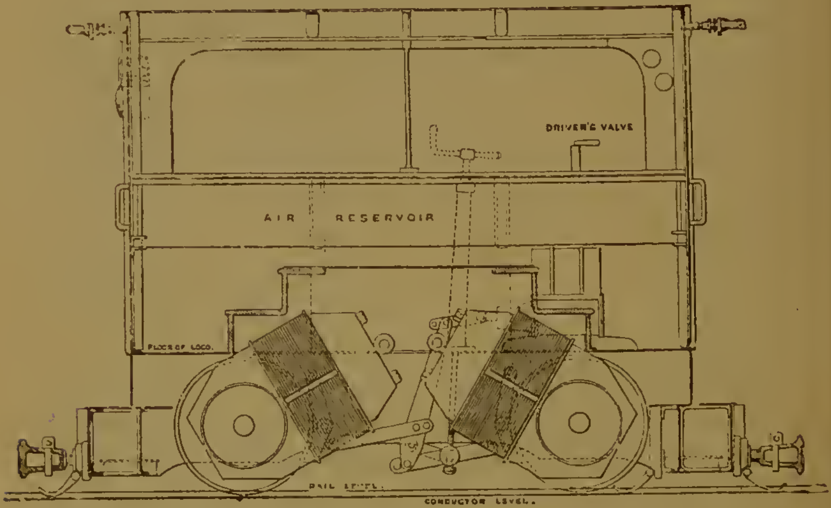

Fig. 369.—City and South London Electric Locomotive.

Each locomotive weighs about 10 tons, and can exert a tractive pull of 3,000 lbs. when running at a speed of 25 miles per hour; at this speed the armature runs at 310 revolutions per minute. A train consists of a locomotive and three carriages, carrying about 100 passengers. The carriages are electrically lighted by glow-lamps supplied with current from the power mains. It is curious to observe how these lamps suddenly become dim when the current is first switched on to the motors of a train standing still. The explanation lies in the phenomena previously referred to, namely, the absence of a back pressure or E.M.F. in the stationary armature, and the consequent heavy rush of current on closing the circuit. Notwithstanding the interposition of resistances to reduce the effect, the current taken is sufficiently great to appreciably reduce the potential difference between the mains at the point affected, and this reduced P.D. is at once shown by the dimly glowing lamps. As the speed increases and the P.D. resumes its normal value, the lamps return to their proper brilliancy.

That the City and South London Electric Railway is a popular success is proved by the fact that it carries 6¼ millions of passengers per annum. During the busy parts of the day, morning and evening, 16 or 17 trains per hour are run in each direction, the total number of train-miles per annum being about 450,000, at a running cost of 6·2 pence per mile. Notwithstanding these evidences of success, the dividends as yet paid to the shareholders have not been very large, one cause probably being that the line is entirely isolated, and has no traffic connections with the railway systems of the country.

The other example of heavy railway electrical engineering in this country is the Liverpool Overhead Railway, a line which runs for over five miles along the line of docks at Liverpool. As will be seen by reference to Fig. 370, which represents one of the stations, this line has all the appearance of an ordinary railway line, the only notable difference, at least till a train comes into sight, being the presence of the insulated third rail lying between the other two. It was opened for traffic in March, 1893.

The line is built almost entirely of iron and steel, and consists of an arched-plate flooring resting on main-girders, which are supported by vertical columns. No ballast is used. There is one swingbridge which, when opened, allows shipping to pass into a dock on the land side of the line, and there are also two or three tilting bridges which can be raised to allow of the passage of specially bulky traffic across the road below.

The power-station is placed near the centre of the line, and contains four compound horizontal steam engines, each capable of giving 400 horse-power at a speed of 100 revolutions per minute. Each of these drives by means of ropes an Elwell-Parker dynamo which, when running at a speed of 400 revolutions per minute, can give a current of 475 ampères at 500 volts. The dynamos are shunt-wound, and have a double magnetic circuit similar to that shown in Fig. 129, but in this case the magnets are vertical instead of horizontal.

From the dynamos the current is taken to a simple switchboard which admits of all the dynamos being coupled together in parallel, so that if required a current of 1,900 ampères at a pressure of 500 volts could be supplied to the line; but with twelve trains running the average current required is only about 700 ampères, and the maximum current about 1,050 ampères. This variation in the current is due to the large current required by a motor at the moment of starting, as already explained. The percentage of variation in the current taken by a particular motor is, of course, much greater than is indicated by the above figures, but since all the trains are not starting at the same instant the percentage variation shown by the ammeters in the power-house is greatly reduced. The influence of the number of trains in smoothing down the variation is curious and interesting. Thus with seven trains the maximum current is 100 per cent. greater than the average, whilst with twelve trains it is only 50 per cent. as above given.

From the power-house the current is taken, without feeders, to the insulated rail S shown in section in Fig. 371

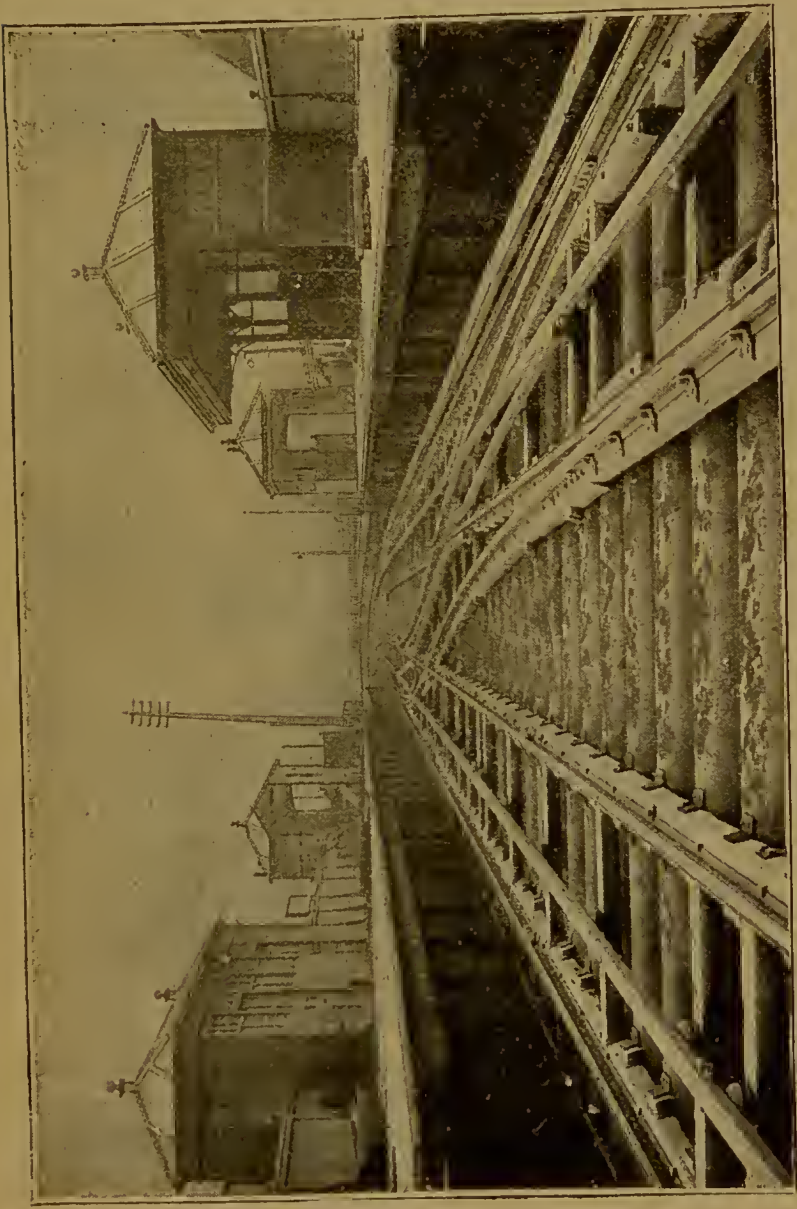

Fig. 370.—The Liverpool Electric Overhead Railway.

and on a larger scale in Fig. 372. This rail is made of a special kind of steel which has high conductivity as compared with other qualities of steel, but does not approach copper in this respect. The cross-sectional area of this conductor is four square inches, and it rests, with a sheet of lead L interposed, on porcelain insulators P, supported by special cross-bearers B and C. The special cross bearers are rendered necessary because the ordinary cross-sleepers are not used to support the traffic rails R R, which are run on longitudinal sleepers, a system originally advocated by

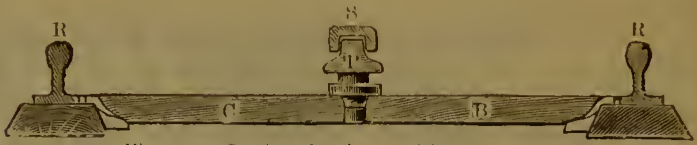

Fig. 371.—Section showing Position of Mid-Rail.

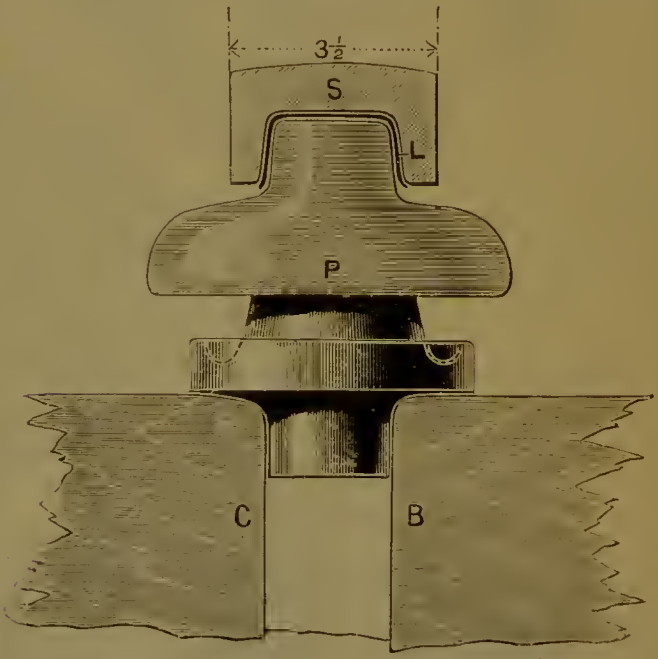

Fig. 372.—Mounting and Insulation of Mid-Rail.

Brunel, and largely used on the Great Western Railway. The working surface of the conductor is seven-eighths of an inch above the level of the traffic rails, in order that the sliding shoe which picks up the current may pass safely over the latter at the crossing points. This is necessary because the traffic rails are used to complete the return circuit, and if the slider were to touch both at the same time it would practically short-circuit the dynamos, with disastrous consequences. To diminish the resistance of the insulated conductor the joints are carefully bridged by copper strips T T (Fig. 373), the ordinary rails S S also being electrically jointed together to diminish the resistance of the return path.

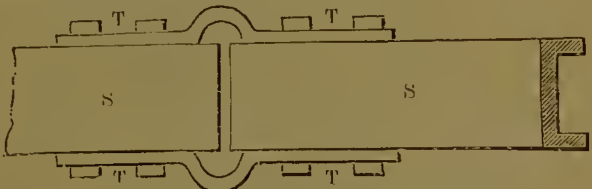

Fig. 373.—Conducting Joints on Steel Rail.

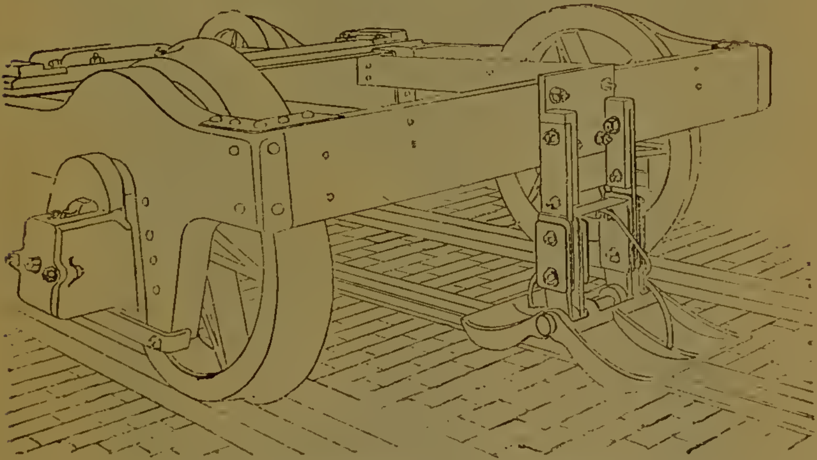

Fig. 374.—Sliding Block for Picking up the Current.

The current is picked up from the insulated conductor by a massive cast-iron block or shoe hinged to an insulated support carried by the bogie frame as represented in Fig. 374. In order that the hinge may not introduce resistance into the circuit, it is electrically bridged by the short flexible cables shown in the figure. From the shoe the current is led through the necessary switches and regulating resistances to the motor, which is mounted on the same bogie frame.

The motors are series-wound, with a drum-armature built upon the running axle of one pair of the bogie wheels (Fig. 375). The field-magnets are of the double magnetic circuit type, and are slung in a horizontal position by strong spiral springs from the framework of the bogie. A speed of one mile per hour is attained by ten revolutions of the axle per minute, so that, when the train is running at 30 miles per hour, which is the maximum speed required, the motor armature is running at 300 revolutions per minute.

Each train carries a motor on the leading and the trailing bogie, but for ordinary running only the motor on the leading bogie is used. At the end of a trip the driver changes ends with the guard, and switches in the other motor for the return trip.

A train consists of two carriages, weighing 40 tons, and capable of carrying 57 passengers, with through connection from end to end. Each carriage is 45 feet long, and is supported by two four-wheel bogies. At present the number of passengers carried is about five millions per annum, and out of 46,429 trains run, no fewer than 95·35 have been up to time, a record difficult to equal on a steam railway. The contractors who undertook the work guaranteed to run the trains at the very low price of fourpence per train-mile for two years, but so satisfactory was the first year's working, that the railway company at the end of it took over the plant and released the contractors from their guarantee, being convinced that the cost had been brought well within the above figure.

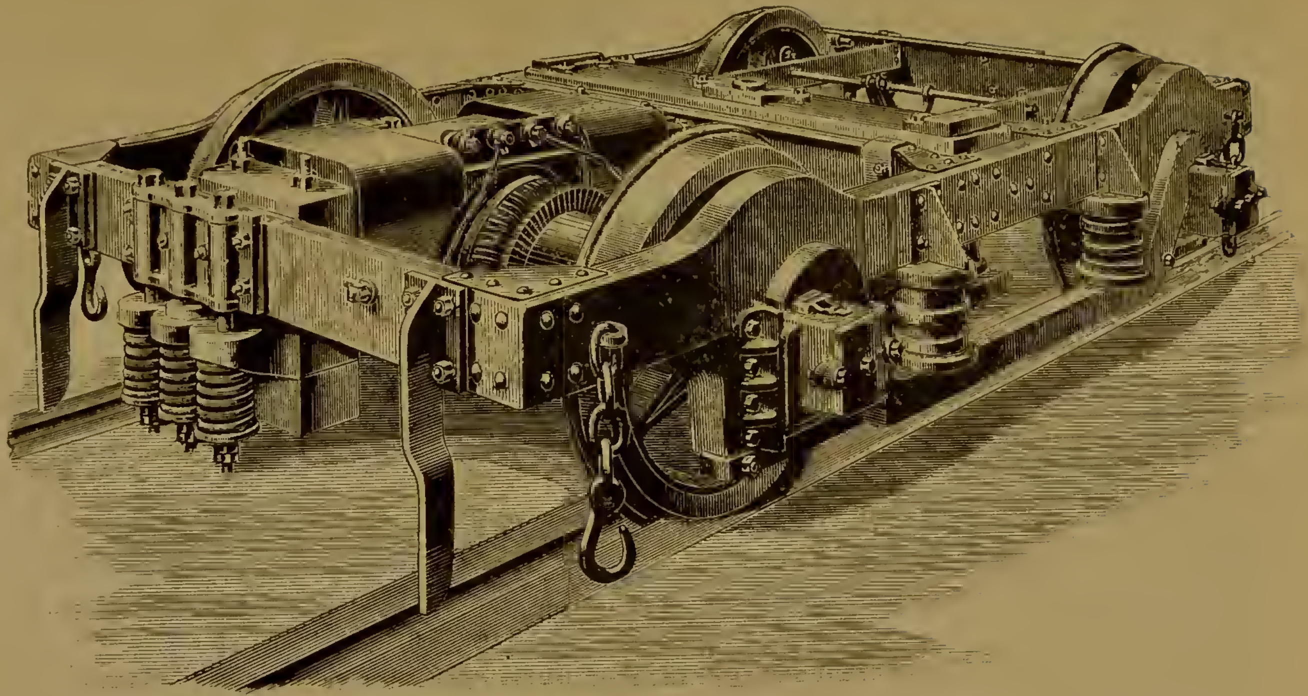

FIG. 375.—THE MOTOR MOUNTED ON THE BOGIE.

One of the most interesting features of the railway is that the signals are worked electrically by the trains themselves, so that no signalmen are required along the line. Each train carries a striking bar, which acts upon contacts placed at the side of the track. For signalling purposes the line is divided up into sections, and the contacts are so arranged that when a train leaves a section it automatically sets the signals so as to block that section until it has itself passed off the section in front, in doing which, it again automatically removes the block previously signalled.

The current for working the signals is supplied by secondary batteries, of which there are two, consisting of 27 cells each, at every station. Of these two batteries one can be used for working purposes, whilst the other is being charged. There are two charging circuits, one for the stations to the north of the power-station, and the other for the stations to the south. All the stations on one circuit are put in series for charging, so that the full pressure of 500 volts may be taken direct from the main switchboard. The storage batteries also supply current for the glow lamps used for lighting the stations, and also for the glow lamps in the signal lanterns. In the latter cases there are duplicate glow lamps in each lantern, so that if one gives way during the night, the other still exhibits the signal.

The manifold advantages of the electric current for railway working are well exhibited in the above description. To sum up, not only does the current supply the power required to drive all the trains on the lines, but it also lights up the stations and carriages at night, and works and lights up the signals. In the latter case signalmen are dispensed with, and each train automatically works and clears the signals as it travels along, thus rendering collisions impossible except through gross carelessness on the part of the driver in disregarding signals. This last possible source of danger can also be eliminated by a method devised by Professors Ayrton and Perry, in which not only does the train set the signals against the section behind it, but actually disconnects that section from the power mains, so that if a train should be carelessly run on to a blocked section it would be powerless to proceed, as it would be deprived of the current which drives its motors until the train in front had passed on to the next section but one. All these varied functions of the current are fulfilled, in the cases described, by currents generated in a single power-station, by one set of engines and generating dynamos, so that the skilled attendance required is economically concentrated in one place.

The success of the City and South London and the Liverpool Overhead Electric Railways has led to the projection of numerous other schemes, some of which have already obtained Parliamentary sanction. It is therefore very probable that the next few years will witness a rapid development in this form of locomotion, especially for intra-urban traffic.

Telpher Lines.—No description of the present position of electric locomotion would be complete without some reference to a system devised as long ago as 1882 by Professors Fleeming Jenkin, Ayrton and Perry. This system has received the very appropriate name of Telpherage, and was originally intended only for the automatic electrical transport of such goods and merchandise as could be conveniently divided into small quantities of from 2 to 5 cwt. each. But it is manifestly applicable to still heavier work, and has been so developed by the Sprague Electric Railway and Motor Company in the United States, whilst an experimental line for the conveyance of passengers was erected and worked at the Edinburgh Electrical Exhibition in 1890.

The distinguishing feature of the system, as originally devised, is that the trucks for carrying the goods are hauled by an electric motor along an overhead steel rod or rope, the electrical arrangements for the supply of energy being such that no driver, guard, signalman or attendants are required during transit. Each train, as it were, takes care of itself by automatically blocking the line behind it in a way already referred to as being possible. Fig. 376 is taken from a photograph of a part of a Telpher line erected for commercial work at Glynde, in Sussex, about 1884. The work to be done consisted in carrying clay for the Sussex Portland Cement Company for a distance of about a mile to the railway across some meadows, where, for various reasons, a line of metals laid on the ground would not have been so advantageous.

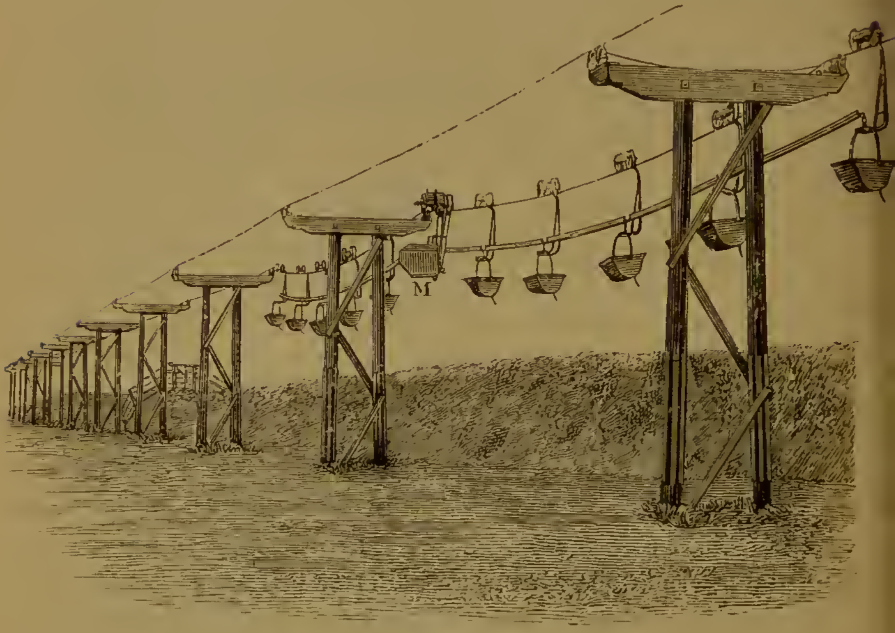

Fig. 376.—The Glynde Telpher Line.

The line consisted of a double set of steel rods, one for the "up" and the other for the "down" line, supported on posts as shown. The rods were 8 feet apart, with a span of about 66 feet, at a height of 18 feet from the ground. The train shown consists of ten trucks or skips, the electric motor being placed in the middle of the train.

The system by which such a train is supplied with electric power is exceedingly interesting and ingenious. The current is brought to the motor by an insulated conductor, and taken back to the generating station by an uninsulated one. But the whole train is on one line of wire, and only makes contact with this line. How then is the necessary electrical potential difference maintained at the terminals of the motor? By the simple device of electrically insulating the successive spans from one another, and making them *alternately* portions of the positive and negative sides of the electric system. In short, the wire in one span brings the current to the motor, and the wire in the next takes it away. To do this, it is only necessary to cross-connect the different spans at the posts, in the manner shown in the annexed diagram (Fig. 377). In this diagram D represents the dynamo, the positive pole of which is connected to the spans A_1, B_2, A_3, B_4, &c.; whilst the negative pole is connected to the alternate spans B_1, A_2, B_3, A_4, &c. Two wheels on each train, a leading wheel L, and a trailing wheel T, are at such a distance apart that one of them is on one span, whilst the other is on the adjacent span. These wheels are insulated and connected by conductors to the terminals of the motor, and thus when resting on successive spans, a current passes from one to the other through the motor. Thus the current for the

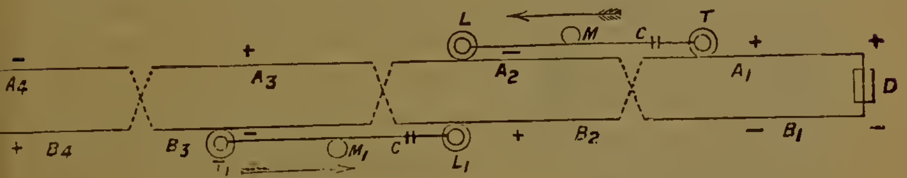

Fig. 377.—Electrical Connections on the Telpher Line.

train L T, which is travelling from right to left, takes the path $D\ A_1\ T\ M\ L\ A_2\ B_1$ back to the dynamo D, whilst the current for the train $L_1\ T_1$ travelling in the opposite direction, flows in the circuit $D\ A_1\ B_2\ L_1\ M_1\ T_1\ B_3\ A_2\ B_1$ back to D. The trains are, therefore, electrically in parallel. There is a short space, when the wheels L and T are passing the posts, during which the train is deprived of current, but its momentum is quite sufficient to carry it past these points.

To prevent the speed becoming excessive, there is attached to the motor an ingenious centrifugal governor, which breaks the circuit completely at a pre-arranged speed. If the speed still further increases, as it might do were the train running down a gradient, a centrifugal brake is brought into action to moderate it.

When the "automatic block," to which reference has been made, is used, the current is supplied in a somewhat different manner. A well insulated conductor runs alongside the working conductor on which the sliding contacts rest. This working conductor is divided into short sections insulated from one another, and these sections are brought into contact with the continuous well-insulated conductor by the train itself as it passes along. By using appropriate electromagnetic devices the train can not only bring its own section into contact with the "live" conductor, but can disconnect the section immediately behind it.

Electric Launches.—Tramways and railways by no means exhaust the successful application of electric power for purposes of locomotion. Ordinary omnibuses, dogcarts, tricycles, launches, &c., have all, from time to time, been driven by the power supplied by electric currents. Since in these cases the vehicle has to carry its supply of energy with it, secondary batteries are practically the only current generators available, and the remarks previously made regarding their excessive weight for the power supplied when used on tramcars, apply with much greater force to most of the above applications. It is therefore not at all surprising that although the various problems have been successfully solved experimentally, the commercial solution cannot yet be regarded as satisfactory, and therefore these applications have not yet come into ordinary and general use.

There is, however, one important exception, where a heavy dead-weight, though undesirable in itself, except for ballasting, is not an insuperable obstacle. This is when the power is employed to propel boats, launches, or other small craft on rivers or lakes, or in the smooth waters of a harbour. So advantageous from many points of view is the use of electric power for such purposes, that it has become very popular, and quite a large fleet of electrically-propelled small craft is now in existence. As compared with steam or oil-driven craft, there is an entire absence of dirt, noise, heat, and smell, and the deck is quite free and clear for the use of passengers. The greatest drawback is that the energy stored only suffices for a ten or twelve hours' run, at the end of which the craft becomes disabled unless a charging current is available. The difficulty has been met on the Thames by the establishment of charging-stations at convenient points along the banks, so that quite a long journey is possible on this river in an electric launch. Since an ordinary charge suffices for a day's run, the launch can be brought at nightfall to one of the charging-stations, and will in the morning be ready for another day's work.

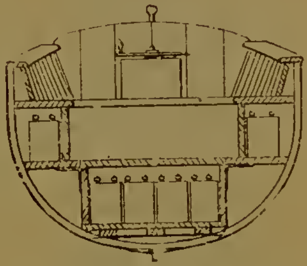

Fig. 378.—Mid-ship Section of E.P.S. Launch.

The secondary cells used in electric launches are specially constructed for the purpose, so that they can be stowed away in the space which can be easily provided for them beneath the seats and under the deck of the launch. The position of the battery and motor in an electric launch

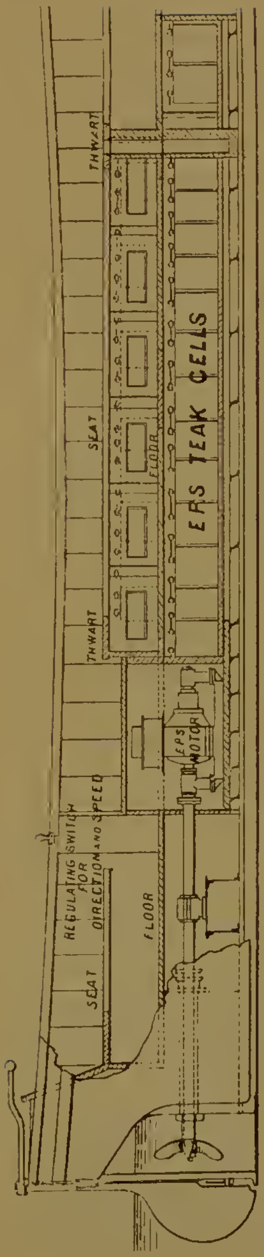

Fig. 379.—Longitudinal Section of E.P.S. Launch.

belonging to the Electrical Power Storage Company is shown in Figs. 378 and 379. The first is a mid ship section of the launch looking aft, and shows the cells placed, some below the deck and others at the side underneath seats, &c. In both positions they are out of the way, and do not interfere with the use of the launch. The second figure again shows the position of the cells, but is further interesting as showing how the motor is directly coupled to the screw shaft, and how the whole of the machinery, except the regulating switch, is stowed away out of sight. It may here be remarked that an electric motor is *par excellence* the proper kind of motor to drive a screw propeller, since the motor armature has a rotary motion and runs best at a high speed; it can therefore be directly coupled to the propeller without the intervention of speed-reducing and power-wasting gear. The regulating switch is arranged to couple the batteries in various ways as may be required, and also to reverse the direction of rotation of the motor armature. Thus the boat is completely under the command of the coxswain, who has his various controlling devices all within easy reach. There were used in all on this launch 66 cells, capable of giving 18 ampères at 30 volts, and at full speed the motor running at 500 revolutions per minute was able to drive the launch at the rate of 11½ miles per hour.

Other Applications of Electric Power.

Space will not allow us to give details of the very numerous applications of electric power to other purposes than those of locomotion, but a very brief summary of the most important of these may prove interesting.

In nearly all the operations of **mining**, electrically-transmitted power is daily being proved to have many advantages over other forms of power. It can be used in the first instance for *drilling and cutting* the rocks and minerals, and then for *hauling* them to the base of the shafts, whence an electric winding engine can *lift* them to the surface. Moreover the *pumps* for keeping the mine clear of water, and the *fans* for maintaining the ventilation, can be driven electrically. All these varied operations have been successfully carried out in practice, and a rapid development of the application of the electric current to mining requirements is now in progress.

In **factories and workshops** the use of electric motors for driving separate machines, or groups of machines, that are only put in motion intermittently, is in many cases more economical than the use of long lines of shafting, and sometimes of subsidiary steam engines. More especially is this the case where the motion required is rotary, as in lathes and drilling machines.

Then again for **cranes** of all kinds electric power is proving itself to be both convenient and economical, and much superior to power transmitted by ropes or long lines of shafting. As a special branch of this particular application it may be noticed that **lifts**, or **elevators**, as our American cousins call them, in hotels and private houses, are easily worked by electrical power.

Our lady readers may also be interested in learning that **sewing machines** can easily be driven by small electric motors, controlled by the movement of a little switch placed within reach of the worker.

Conclusion.

Here we must stop. A full list of all the further applications of the electric current would prove tedious. Enough has been said to show that here we have, if the latest, certainly the most pliable of all the servants which man has harnessed for his own purposes. Whether we consider the mysteries which still surround the simplest actions of this obedient servant, mysteries which have defied the searching enquiries of the subtlest intellects of our time; or turn to contemplate the marvellous range of its activities, from transmitting the feeblest whisper a thousand miles to whirling along the ponderous train on a railway; —the human mind cannot but be lost in wonder and amazement, and must feel bound to confess that the servant, though willing and obedient beyond the dreams of the poet, still remains more mysterious and elusive than the magi and spirits of the Arabian Nights.

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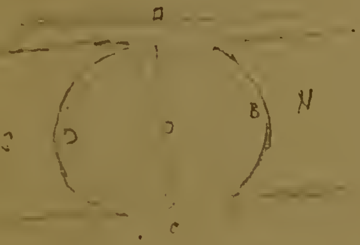

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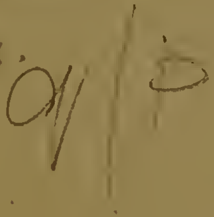

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